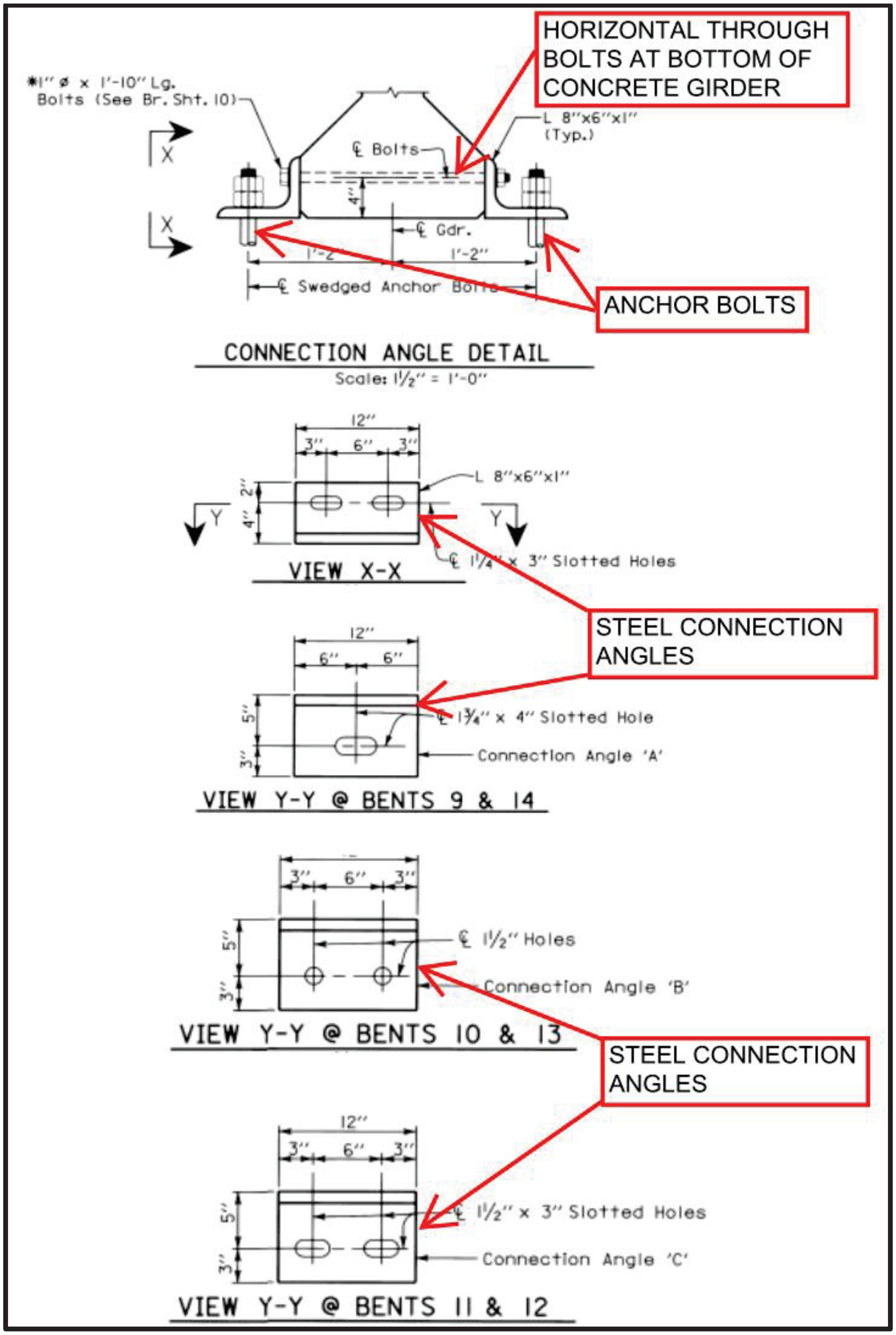
Figure 69: Steel Connection Angle and Bolt Details between Bents 9 and 14 on the Bridge to I-10 Eastbound at Exit 30[246]



[246] Source: ALDOT, 2006 (as modified)

Since all the bents between Bents 9 and 14 are relatively similar in structure, this analysis focuses on the surge effects at only two bents (rather than at all six bents). An analysis of all the bents on this ramp would be recommended if it was decided to implement construction efforts to resist storm surge effects properly. Bent 11 was chosen to represent a typical bent for the section with three piles supporting 50 foot (15.2 meter) spans on either side of the bent. The second bent, Bent 13 was selected because it is unique and has six piles, rather than the typical three piles, and has a wider pile cap than the typical bent. Key elevations for Bents 11 and 13 are provided in Table 30.

Table 30: Key Elevations at Bents 11 and 13 on the Bridge to I-10 Eastbound at Exit 30

	Mean Sea Level Elevation[247] Feet (Meters)	MHHW Elevation Feet (Meters)	Bottom of Lowest Beam Elevation[248] Feet (Meters)	Highest Top of Deck Elevation[249] Feet (Meters)	Depth of Water Feet (Meters)	Mud Elevation[250] Feet (Meters)	Bottom of Pile Elevation Feet (Meters)
Bent 11	0.3 (0.1)	1.1 (0.3)	6.3 (1.9)	11.0 (3.3)	2.0 (0.6)	-1.7 (-0.5)	-72.7 (-22.2)
Bent 13	0.3 (0.1)	1.1 (0.3)	9.2 (2.8)	13.8 (4.2)	2.0 (0.6)	-1.7 (-0.5)	-73.7 (-22.5)

Step 3 – Identify Climate Stressors That May Impact Infrastructure Components

Storm surge in combination with sea level rise is a major concern for the facility. Any low lying facility such as this that is already relatively close to MHHW could be greatly impacted by storm surge and sea level rise. Historical storms have illustrated the threat: the storm surge caused by Hurricane Katrina dislodged the deck and girders of the ramp six feet (1.8 meters) to the north.[251]

Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes

Three storm surge scenarios were developed for the assessment of storm surge-related impacts and infrastructure vulnerability. These consist of the following:

- **Hurricane Katrina Base Case Scenario**: This scenario represents the surge conditions that actually occurred in Mobile with Hurricane Katrina making landfall at the Louisiana-Mississippi border.

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[247] Mean sea level is the average of the water elevations recorded at each hour of the day over the current National Tidal Datum Epoch. The tidal epoch is the specific 19-year period over which NOAA uses to obtain observations that are used to develop tidal statistics.
[248] Due to the deck cross slope, the lowest beam elevation occurs at Beam 1, the beam closest to the inside face of the north parapet.
[249] Due to the deck cross slope, the highest top of deck elevation occurs at the top concrete deck surface at the base of the inside face of the south parapet.
[250] Mud elevation is the elevation of the top of the soil which is below the water surface.
[251] Cuomo, Shimosako, and Takahashi, 2009

- **Hurricane Katrina Shifted Scenario**: This scenario estimates the surge levels that would occur if Hurricane Katrina's path was shifted east to make landfall in Mobile.
- **Hurricane Katrina Shifted + Intensified + Sea Level Rise (SLR) Scenario**: This scenario estimates the surge levels that would occur if Hurricane Katrina was shifted, intensified with stronger winds due to climate change, and came on top of 2.5 feet (0.8 meters) of sea level rise.

A more detailed description of each scenario and how it was developed can be found in Section 4.4.4 of this document (under Step 4) and in the *Climate Variability and Change in Mobile, Alabama* report.[252] Table 31 shows the key storm surge characteristics at Bent 11 under each scenario. Table 32 shows this same information for Bent 13.

Table 31: Storm Surge Characteristics at Bent 11 on the Bridge to I-10 Eastbound at Exit 30 by Scenario

Storm Surge Scenario	Storm Surge Model Results[253]			Wave Model Results[254]		
	Water Surface Elevation Feet (Meters)	Sustained Wind Speed MPH (KPH)	Depth Averaged Current[255] Knots (KPH)	Wave Height[256] Feet (Meters)	Peak Wave Period[257] Seconds	Wave Direction Compass Degrees[258]
Hurricane Katrina Base Case	12.8 (3.9)	74 (119)	2.6 (4.8)	6.2 (1.9)	7.7	7
Hurricane Katrina Shifted	20.0 (6.10)	104 (167.3)	4.3 (8.0)	8.9 (2.7)	8.3	7
Hurricane Katrina Shifted + Intensified + SLR	24.9 (7.59)	110 (177.0)	4.4 (8.1)	4.4 (1.3)	8.3	7
FEMA[259] Base Flood Elevation (100-yr Flood Level)	17.0 (5.2)	-	-	-	-	-

[252] USDOT, 2012
[253] Simulations of storm-induced water levels (i.e., storm surge) and associated currents were performed using the two dimensional depth average version of the ADvanced CIRCulation model, ADCIRC.
[254] The wave characteristics accompanying each of the storm surge scenarios were simulated using the STeady State spectral WAVE (STWAVE) model.
[255] The two dimensional (depth averaged) version of the ADCIRC model calculates currents that represent the average current over the total depth at any given location. Thus, effects such as wind driven current variation with depth or smaller currents near the seabed are not included in the results.
[256] Zeroth moment wave height, H_{mo}, is equal to 4.0*square root (m_o) where m_o is the zeroth moment of the wave spectrum. For more detail refer to NOAA, 1996. In deep water the zeroth moment wave height is equal to the "significant wave height", Hs, which is the average of the highest one third of waves in a random wave field. In shallow water the significant wave height may be up to ten percent higher than H_{mo} (USACE, 2002).
[257] Peak wave period, Tp, is the period corresponding to the frequency band with the maximum value of spectral density in the non-directional wave spectrum as described in NOAA, 1996.
[258] Waves are propagating toward the indicated direction. Thus, zero degrees imply waves are propagating northward, whereas 90 degrees imply waves are propagating eastward.
[259] FEMA, 2007b

Table 32: Storm Surge Characteristics at Bent 13 on the Bridge to I-10 Eastbound at Exit 30 by Scenario

Storm Surge Scenario	Storm Surge Model Results[260]			Wave Model Results[261]		
	Water Surface Elevation Feet (Meters)	Sustained Wind Speed mph (kph)	Depth Averaged Current[262] Knots (kph)	Wave Height[263] Feet (Meters)	Peak Wave Period[264] Seconds	Wave Direction Compass Degrees[265]
Hurricane Katrina Base Case	12.8 (3.9)	74 (119)	2.3 (4.3)	6.2 (1.9)	7.7	7
Hurricane Katrina Shifted	20.0 (6.1)	104 (167)	3.9 (7.2)	8.9 (2.7)	8.3	7
Hurricane Katrina Shifted + Intensified + SLR	24.6 (7.5)	110 (177)	4.2 (7.8)	4.4 (1.3)	8.3	7
FEMA[266] Base Flood Elevation (100-yr Flood)	17.0 (5.2)					

Figure 70 shows the FEMA regulatory floodplain for the bridge crossing locations. The FEMA mapping shows a storm surge elevation of 17 feet (5.2 meters) at the bridge location. The crossing is in FEMA Zone VE, which is defined as an area of inundation with additional hazards due to storm-induced velocity wave action.

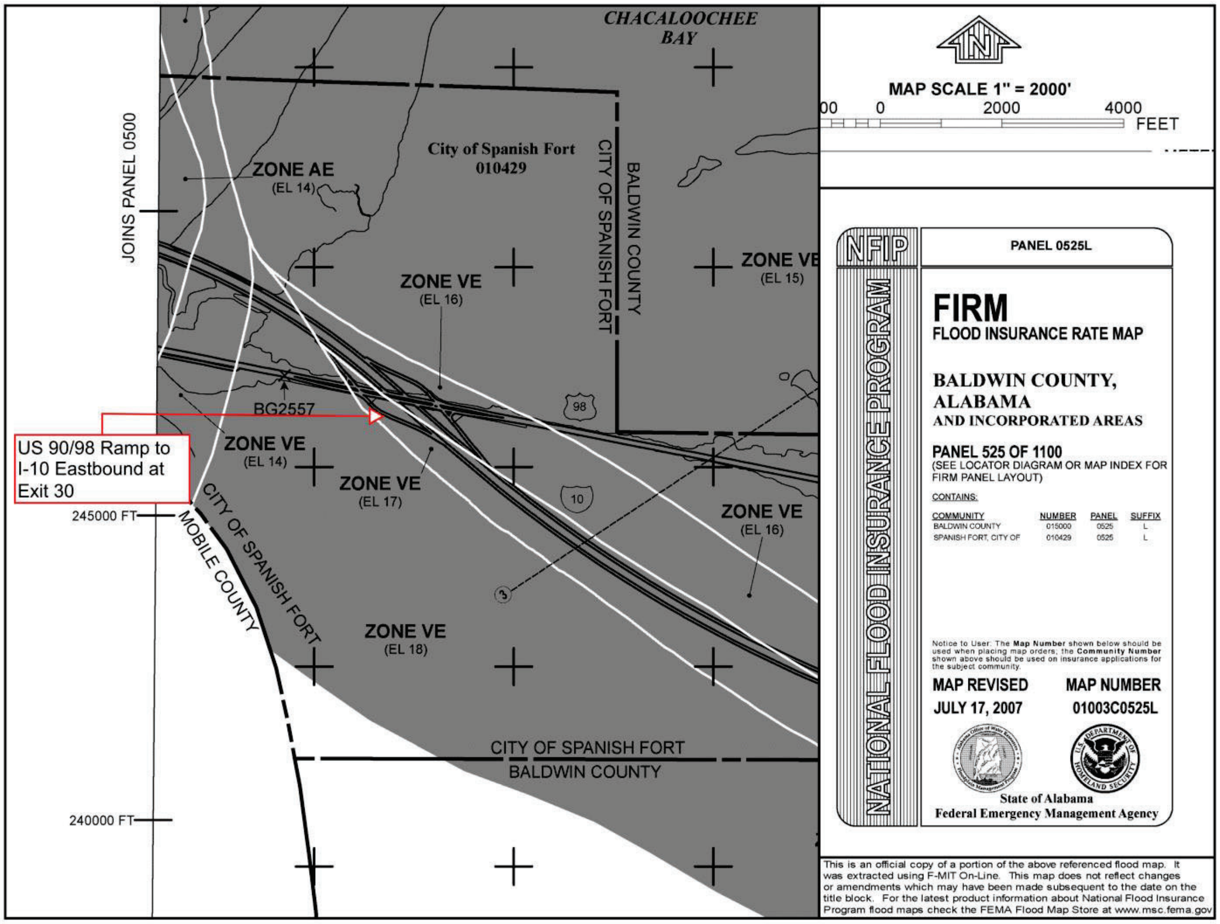
Step 5 –Assess Performance of the Existing Facility

To assess performance of the case study bridge under storm surge forces, three general failure modes were examined:

- **Failure Mode One** – The superstructure fails by wave uplifting and it washes away. It is assumed the deck slab and girders remain intact and that failure would occur at the superstructure-bearing components.[267]

[260] Simulations of storm-induced water levels (i.e. storm surge) and associated currents were performed using the two dimensional depth average version of the ADvanced CIRCulation model, ADCIRC.
[261] The wave characteristics accompanying each of the storm surge scenarios were simulated using the STeady State spectral WAVE (STWAVE) model.
[262] The two dimensional (depth averaged) version of the ADCIRC model calculates currents that represent the average current over the total depth at any given location. Thus, effects such as wind driven current variation with depth or smaller currents near the seabed are not resolved in the results.
[263] Zeroth moment wave height, H_{mo}, is equal to 4.0*square root (m_o) where m_o is the zeroth moment of the wave spectrum. For more detail refer to NOAA, 1996. In deep water the zeroth moment wave height is equal to the "significant wave height", Hs, which is the average of the highest one third of waves in a random wave field. In shallow water the significant wave height may be up to ten percent higher than H_{mo} (USACE, 2002).
[264] Peak wave period, Tp, is the period corresponding to the frequency band with the maximum value of spectral density in the non-directional wave spectrum as described in NOAA, 1996.
[265] Waves are propagating toward the indicated direction. Thus, zero degrees imply waves are propagating northward, whereas 90 degrees imply waves are propagating eastward.
[266] FEMA, 2007b
[267] Superstructure bearing components are typically bearing elements that connect the bottom of the girders or beams to the pier cap.

Figure 70: FEMA Flood Insurance Rate (FIRMette) Map for the Bridge to I-10 Eastbound at Exit 30[268]



- **Failure Mode Two** – The substructure[269] fails due to lateral forces applied from the waves or gets uprooted by the upward vertical forces acting on the superstructure. The majority of the lateral and vertical wave loads act on the superstructure and are transmitted to the substructure. Substructure conditions with and without scour were calculated and analyzed. In the analysis of this failure mode, it is determined if the substructure will remain intact with the superstructure attached.
- **Failure Mode Three** – The substructure fails due to excessive scour. Excessive scour at any bridge foundation leads to bridge instability and eventual failure. There are also different types of scour (which are discussed below) that can occur at a bridge foundation. Each storm surge scenario is investigated with and without scour. The scour is assumed to be caused by the particular storm surge scenario being investigated.

Under all three storm surge scenarios described in Step 4, the superstructure and substructure at both Bents 11 and 13 are inundated. Thus, it is assumed that the case study section of the bridge

[268] FEMA, 2007b. Note: The elevations shown are in NAVD88.
[269] The substructure in this case study bridge consists of concrete piles and the pile cap connecting the concrete piles.

will not be used by the public and trucks and cars will not be imposing live load on the structure during the storm surge event. It should also be noted that under the Hurricane Katrina Shifted + Intensified + SLR scenario the sea level rise of 2.5 feet (0.8 meters) would itself place parts of the concrete deck at the beginning of the ramp between Bents 1 and 9 under water. When a portion of the top of the deck is under water, it is assumed that the bridge is out of service until adaptations or remedial actions are put in place.

Design guidance documents used in the analysis of the effects of storm surge (and sea level rise) on bridges include the following:

- American Association of State Highway and Transportation Officials (AASHTO) *Load and Resistant Factor Design (LRFD) Bridge Design Specifications*[270]
- AASHTO *Guide Specifications for Bridges Vulnerable to Coastal Storms*[271]

The *LRFD Bridge Design Specifications* provides the equations used for a structural analysis of a bridge whereas the *Guide Specification for Bridges Vulnerable to Coastal Storms* provides the equations used to develop the wave forces acting on a bridge during a storm surge.

The remainder of this section discusses the assessment of each failure mode for the existing bridge under each of the storm surge scenarios described in Step 4.

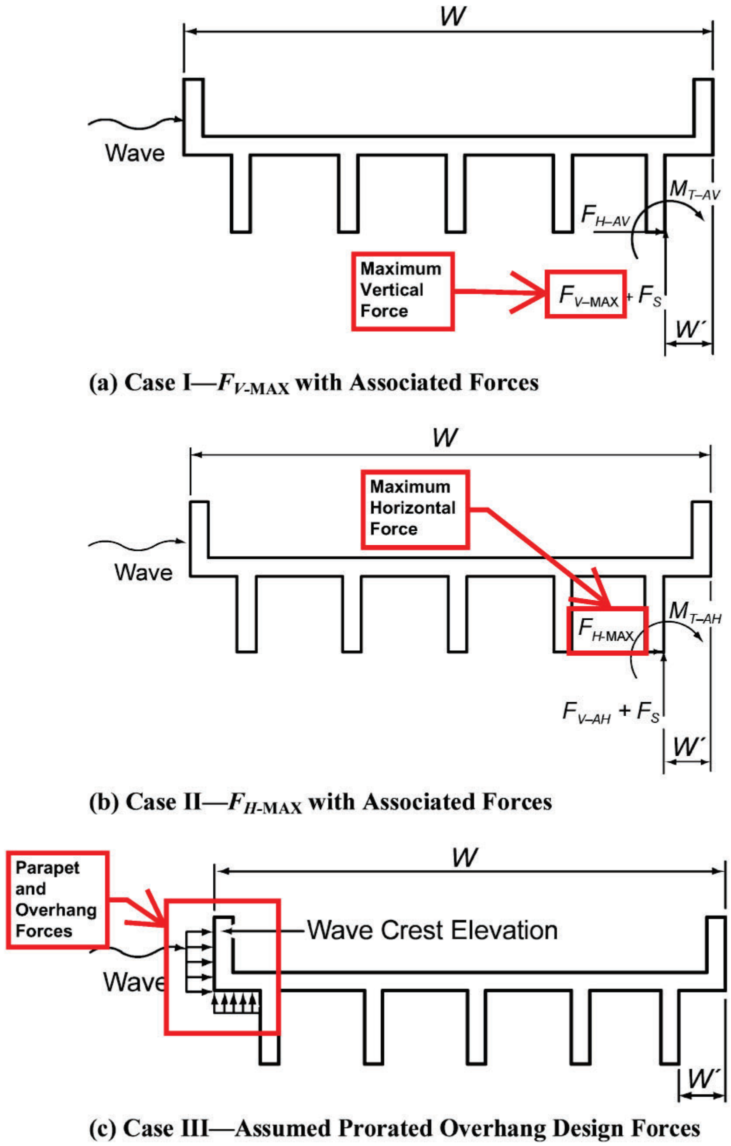
<u>Failure Mode One - Superstructure Failure</u>

A storm surge (with its associated waves) that encounters a bridge imparts vertical and horizontal forces on the superstructure. Typically, it is the combination of both forces that causes a superstructure to fail. The vertical forces include dynamic forces from the waves, a buoyancy force if it submerges the bridge, and a vertical slamming force, which can impact the underside of the superstructure. The horizontal force is the sum of the wave and current induced forces. The *Guide Specification for Bridges Vulnerable to Coastal Storms* provides three Design Cases for a superstructure and the equations (for each Design Case) to determine the vertical and horizontal forces on a superstructure using data from storm surge and wave models (see Figure 71).

Design Case I maximizes the vertical wave force and is used to design the resistance of the superstructure from the substructure. Design Case II maximizes the horizontal wave force and is used to design the resistance of bents and horizontal restraints. Design Case III determines the forces on the overhang and parapet portion of the bridge. Design Case III will not be investigated in this case study because the damage of an overhang or parapet is a localized failure that would not cause the bridge to collapse or place it completely out of service: one might wish to investigate this if a full adaptation assessment were being conducted.

[270] AASHTO, 2012
[271] AASHTO, 2008

Figure 71: Illustration of Superstructure Force Design Cases[272]



It should be noted that determining all the possible modes of concrete failure[273] in the concrete beams and concrete pile cap was beyond the scope of this study. Therefore, it was assumed in this failure mode that concrete failures in the pile cap or in the concrete beams would not occur. For this case study and in all concrete structures, reinforcing bars embedded in properly designed concrete pile caps and in properly designed concrete beams are assumed to sufficiently prevent a concrete failure. Also, a majority of the bridge failures caused by Hurricane Katrina typically failed due to the connection between the superstructure and substructure.[274]

[272] Source: AASHTO, 2008 (Figure 6.1.2.1-1) (as modified)
[273] Concrete failure would be a large spall or shear crack
[274] Curtis, 2007

FHWA002824

In this case study, failure is assumed to occur at either the anchor bolts (embedded into the concrete pile cap, see Figure 69) or horizontal through bolts (located at the bottom of the concrete girders, see Figure 69). For a typical 50 foot (15.2 meter) span, the vertical bolt capacity was 542.6 kips[275] (2,413.6 kilonewtons) and the horizontal bolt capacity was 1,221.4 kips (5,433.1 kilonewtons). These capacities were based on the type and size of bolts as specified in the ALDOT drawings (see Figure 69) and in accordance with the 2012 *AASHTO LRFD Bridge Design Specifications.*

The data shown in Table 31 and Table 32 from the storm surge and wave models were used to calculate wave forces. The various forces were calculated and the load factors[276] in the *LRFD Bridge Design Specifications* were applied before comparing to the capacities of the bolts securing the bridge. Table 33 illustrates the compiled superstructure forces at Bent 11 and Table 34 illustrates the compiled superstructure forces at Bent 13 under each of the storm surge scenarios. Failure of the bolts to secure the superstructure occurs when the applied forces (vertical or horizontal) from the waves exceed the bolt capacity. The tables show the bolts failing from the vertical forces under all the storm surge scenarios in Design Case I for Bents 11 and 13, under the Hurricane Katrina Base Case Scenario in Design Case II for Bent 11, and under all the storm surge scenarios in Design Case II for Bent 13. The bolts do not fail from the horizontal loads in any of the storm surge scenarios.

Vertical and horizontal forces vary between the different storm surge scenarios, Bents 11 and 13, and the two Design Cases. This is due to dynamic wave forces in play, how far under water the superstructure is submerged and the maximum forces each of the Design Cases are trying to calculate. The farther below the water the superstructure is, the dynamic horizontal wave forces are less intense and the water velocity would be less, thus causing the magnitude of the lateral forces to be less. The vertical wave and vertical slamming forces increase the farther below the water superstructure is submerged thus increasing the vertical uplift forces.

To summarize, the superstructure at Bents 11 and 13 would likely have bolt failures at the bottom of the girders and lift off and wash away under all of the storm surge scenarios investigated. Because Bent 11 is typical of the other bents in the case study segment, it is likely that this failure could occur at any of the spans within the study section of the ramp.

[275] One kip, also referred to as a kilopound, is equal to 1,000 pounds-force (4.4 kilonewtons).
[276] Load factors may be thought of as safety factors that are applied to the loads.

Table 33: Superstructure Forces at Bent 11 on the Bridge to I-10 Eastbound at Exit 30

Storm Surge Scenario	Design Case I		Design Case II	
	Applied Vertical Forces kips (kilonewtons)	Applied Horizontal Forces kips (kilonewtons)	Applied Vertical Forces kips (kilonewtons)	Applied Horizontal Forces kips (kilonewtons)
Hurricane Katrina Base Case	5,450.4 (24,244.6)	85.7 (381.2)	1,374.4 (6,113.6)	141.9 (631.2)
Hurricane Katrina Shifted	10,030.5 (44,617.9)	72.3 (321.6)	533.2 (2,371.8)	85.5 (380.3)
Hurricane Katrina Shifted + Intensified + SLR	11,754.3 (52,285.7)	39.1 (173.9)	512.2 (2,278.4)	57.5 (255.8)
Bolt Capacity For Four Girders in a Single Bridge Span, kips (kilonewtons)	542.6 (2,413.6)	1,221.4 (5,433.1)	542.6 (2,413.6)	1,221.4 (5,433.1)
Failure (Yes/No)	Yes, for all scenarios	No, for all scenarios	Yes, for Katrina Base Case	No, for all scenarios

Table 34: Superstructure Forces at Bent 13 on the Bridge to I-10 Eastbound at Exit 30

Storm Surge Scenario	Design Case I		Design Case II	
	Applied Vertical Forces kips (kilonewtons)	Applied Horizontal Forces kips (kilonewtons)	Applied Vertical Forces kips (kilonewtons)	Applied Horizontal Forces kips (kilonewtons)
Hurricane Katrina Base Case	3,591.5 (15,975.8)	107.8 (479.5)	1,478.4 (6,576.3)	181.9 (809.1)
Hurricane Katrina Shifted	8,637.0 (38,419.3)	83.8 (372.8)	787.1 (3,501.2)	102.7 (456.8)
Hurricane Katrina Shifted + Intensified + SLR	10,245.2 (45,572.9)	38.6 (171.7)	756.6 (3,365.5)	62.8 (279.3)
Bolt Capacity For Four Girders in a Single Bridge Span, kips (kilonewtons)	542.6 (2,413.6)	1,221.4 (5,433.1)	542.6 (2,413.6)	1,221.4 (5,433.1)
Failure (Yes/No)	Yes, for all scenarios	No, for all scenarios	Yes, for all scenarios	No, for all scenarios

Failure Modes Two and Three - Substructure Failure

Failure in the substructure during a storm surge is caused by vertical and / or horizontal loads transferred from the superstructure to the substructure and subsequently overloading elements (in this case study, the concrete piles) of the substructure. In this case study, the vertical and horizontal forces applied to the substructure are derived from the superstructure forces and from the *Guide Specification for Bridges Vulnerable to Coastal Storms*.[277] A geotechnical computer model (simulating soil conditions) was created using GROUP 8.0 software. It uses the forces as inputs, and the results are compared to allowable geotechnical and structural capacities of the pile.

Possible failure modes of the substructure investigated in this case study were:

- **Uplift of the piles and pile cap from vertical wave forces:** Vertical forces are applied and the soil uplift resistance[278] and axial tensile (structural) capacity[279] of the pile are checked for sufficiency
- **Failure of piles from lateral forces:** Lateral forces are applied and piles are checked for shear[280] and bending[281] sufficiency. The geotechnical software, GROUP 8.0, determined the maximum lateral force (shear and bending) on a single pile based on calculated lateral wave forces on the pile cap and the assumed soil profile (with and without scour). This lateral force was then compared to the structural pile lateral capacity (shear and bending) to determine if it passed or failed.

The lateral and axial pile loading analyses were performed in accordance with the procedures outlined in the *Guide Specification for Bridges Vulnerable to Coastal Storm*[282] and the *LRFD Bridge Design Specifications*[283] using various combinations of the wave loads provided for the superstructure and the bents.

This failure modes assume the superstructure is attached to the substructure up to the failure point of the bolts as described in Failure Mode 1. Thus, if the owner of the bridge should decide to reinforce the bolts (or change the bolt configuration) as an adaptation option in response to Failure Mode 1, this mode of failure would need to be re-evaluated. This particular study did not include the effects of a ship collision on a pier (this is covered in the *LRFD Bridge Design Specifications* document) because it is not over a navigable channel. However, the owner may

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[277] AASHTO, 2008
[278] Soil resistance for concrete piles is defined as the resistance derived from soil friction and soil cohesion.
[279] Axial tensile capacity of the pile is defined as the structural capacity of the pile to deal with tension. The concrete piles have a calculated structural tensile capacity of 386 kips (1,717 kilonewtons) in accordance to the *LRFD Bridge Design Specifications* document.
[280] The tendency for a pile to be sheared is caused by the applied horizontal loads. The concrete piles have a calculated structural shear capacity of 55 kips (245 kilonewtons) in accordance to the *LRFD Bridge Design Specifications* document.
[281] Bending is the flexure of the pile caused by the application of horizontal loads. The concrete piles have a calculated structural bending moment capacity (the highest stress experienced within a material under bending at its moment of rupture) of 233 feet-kips (316 kilonewton-meters) in accordance to the *LRFD Bridge Design Specifications* document.
[282] AASHTO, 2008
[283] AASHTO, 2012

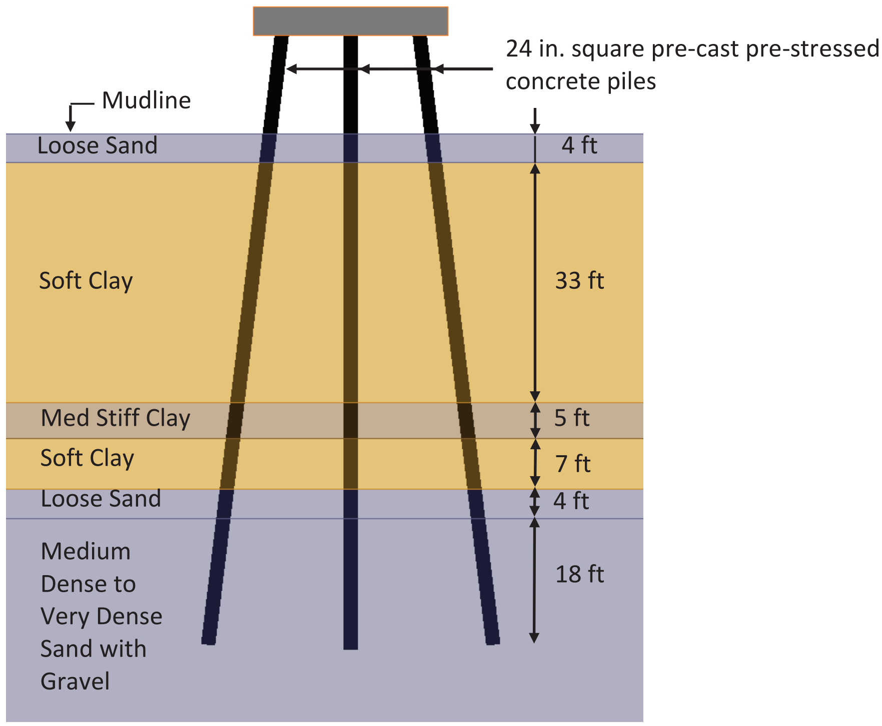
need to evaluate whether vessels or large debris in a storm surge scenario might impact the bridge and whether such an impact should be considered in the bridge design.

The pile dimensions and length were developed based on the as-built plans and the pile driving records. The as-built plans indicate that Bent 11 consists of a single row of three 24 inch (61 centimeter) square pre-cast pre-stressed concrete piles while Bent 13 consists of two rows of three 24 inch (61 centimeter) square pre-cast pre-stressed concrete piles. The pile driving records indicate that the piles were driven to a depth of 71 feet (21.6 meters) and 72 feet (21.9 meters) below the mudline for Bents 11 and 13, respectively.

The subsurface profiles at Bents 11 and 13 were developed from the boring logs provided on the as-built plans. Because no information other than qualitative descriptions of the soil strata is provided on the boring logs (i.e., no Standard Penetration Test (SPT) [284] blow counts or laboratory test results), the engineering properties for the soil layers used in the lateral and axial pile capacity analyses were derived using typical values reported in the geotechnical engineering literature.[285] An initial analysis was performed to calibrate the assumed engineering properties based on an assumption that the foundations at Bents 11 and 13 performed acceptably during Hurricane Katrina (i.e., there was no pull-out of the piles or piles were not forced out of alignment or rotated under the Hurricane Katrina Base Case Scenario). Because the subsurface characteristics were assumed to be similar for Bents 11 and 13, the generalized subsurface profile at Bent 11 is shown as an example below in Figure 72.

[284] The standard penetration test is an in-situ dynamic penetration test designed to provide information on the geotechnical engineering properties of soil.
[285] Duncan, Horz, and Yang, 1989; Holtz and Kovacs, 1981

Figure 72: Generalized Subsurface Profile at Bent 11 on the Bridge to I-10 Eastbound at Exit 30[286]



Scour of the bridge piers is another key consideration in any analysis of substructure failure. Scour occurs by water forces eroding the soil support where a pile and mudline meet, reducing each pier's capacity to handle the forces on it by reducing the embedment length of a pile. Reduction of the embedment length exposes the pile to more stream and wave forces and subjects the pile to increased stresses and reduces pile lateral capacity if the piles are embedded in competent soils. Scour computations were performed for each of the bents following the guidance provided in the Federal Highway Administration's (FHWA) HEC-18[287] publication. Scour at bridge piers is computed as the sum of **contraction scour, long term trends,** and **local pier scour**.

Contraction scour is the general erosion of the channel bed due to the contraction and acceleration of flows as they transition from a wider area into a narrower bridge crossing. The theoretical basis of contraction scour is centered on the acceleration of flows through a bridge opening. Because the study area bridge is bounded to the north by the causeway and a bulkhead shoreline, flows will not be accelerating through this area and contraction scour will be negligible. Pressure scour is also a form of contraction scour that is often a consideration for

[286] Note: No scour conditions is shown and, for clarity, the superstructure is not shown
[287] Arneson et al., 2012

bridges where flooding (or storm surge) conditions result in the bridge deck impeding the flood flow. Under pressure scour, a contraction of flows occurs vertically and the same general theory of accelerating flows causing general scouring of the channel bed occurs. However, in the case of the study site, there is sufficient opportunity for the storm surge to flank the bridge opening, thus raising the water surface on the opposite side of the bridge opening and negating the primary mechanisms for vertical contraction and formation of pressure flow; thus pressure scour is also assumed to be negligible.

A **long term trend** refers to the process where a water body undergoes a long term change in its bed elevation. This change can be thought of as occurring over the course of years or decades, as opposed to occurring during a single storm event as is the case with the other types of scour. In general for most Eastern estuaries, the processes of sea level rise and associated sedimentation is generally expected to result in increasing sea bed elevations.[288] Thus, some degree of sedimentation at the case study bridge is assumed to occur over the long term. However, because of the uncertainty in quantifying future sea bed levels, the analysis of the bridge foundations focuses on current sea bed levels to ensure foundation stability under current conditions, with the potential of improved conditions in the future. Another example of a long term trend would be lateral migration of barrier islands and resulting changes to seabed elevations as inlets expand, close up, and migrate laterally. The Bonner Bridge in the Outer Banks of North Carolina is a classic example. In this particular case, the shoreline has been stabilized with timber bulkheads which minimizes the potential of lateral migration. This type of long term trend is not a factor at this case study facility.

The last component is **local pier scour**. Local pier scour is caused by the vertical obstruction to flows caused by the physical presence of the pier in the water. Local scour occurs as horizontal flow velocity is converted into vertical turbulence caused by water flows going around a pier. The vertical turbulence, known as a horseshoe vortex, effectively removes soil at the base of the pier. Additional turbulent formations known as wake vortices form downstream of the pier in a flow vacuum created opposite the water flow. The wake vortices have a similar effect as the horseshoe vortex in the removal of soil from the backside of a pier foundation. In the case study, the depth of local pier scour was estimated using the Sheppard pier scour equation (also known as the Florida DOT Pier Scour Methodology) which is published in FHWA's HEC-18 manual[289] and Florida's *Bridge Scour Manual*.[290] The Sheppard pier scour methodology has been documented as an improvement over traditional HEC-18 methods as it provides improved considerations for soil material types while still incorporating considerations for flow depth, velocity, and angle of attack into the pier scour computations.

[288] Duncan, Goff, Austin, and Fulthorpe, 2000
[289] Arneson et al., 2012
[290] FDOT, 2011

The axial-lateral loading analysis of the Bent 11 and 13 foundations were performed using a three-dimensional soil-structure interaction analysis software called GROUP 8.0.[291] The results of these analyses show the maximum lateral loads,[292] vertical loads,[293] and bending moment[294] acting on the pile cap and are presented in terms of maximum bending moment,[295] maximum shear force,[296] and maximum tension load[297] action on each individual pile. The maximum tension load is compared with total pile uplift resistance[298] for each pile. The maximum structural axial, shear, and moment loads were compared to the corresponding structural capacity. Table 35 and Table 36 show the inputs to the GROUP 8.0 software, including the calculated scour depths. Results are shown in Table 37 and Table 38 with and without scour considerations for each scenario. Failure of the substructure occurs when either vertical uplift forces exceed the vertical soil resistance or structural tensile capacity of the piles causing a pile to pull out or lateral forces exceed lateral geotechnical or structural capacity of the pile causing a pile to deflect excessively or break.

291 Reese, Wang, Arrellaga, Hendrix, and Vasquez, 2010
292 Lateral loads are the applied horizontal loads.
293 Vertical loads are the uplift forces derived from upward wave forces acting on the superstructure.
294 Bending moment is a flexure force on a pile section caused by the applied horizontal loads.
295 Maximum bending moment at each pile is determined after compiling all loads (for a particular storm surge scenario) into the GROUP 8.0 computer model. This process is performed for each of the three storm surge scenarios.
296 Maximum shear force at each pile is determined after compiling all loads (for a particular storm surge scenario) into the GROUP 8.0 computer model. This process is performed for each of the three storm surge scenarios.
297 Maximum tension load at each pile is determined after compiling all loads (for a particular storm surge scenario) into the GROUP 8.0 computer model. This process is performed for each of the three storm surge scenarios.
298 Total pile uplift resistance is derived from soil friction and soil cohesion acting on the pile.

Table 35: Substructure Input Loads at Bent 11 on the Bridge to I-10 Eastbound at Exit 30

Storm Surge Scenario	Scour Depth Feet (Meters)[299]	Axial Tension Load kips (kN)	Lateral Load kips (kN)	Bending Moment Kip-Ft (kN-meter)
Hurricane Katrina Base Case	No Scour	543 (2,415)	165 (734)	62 (84)
	3.1 (0.9)			
Hurricane Katrina Shifted	No Scour	543 (2,415)	117 (520)	100 (136)
	4.7 (1.4)			
Hurricane Katrina Shifted + Intensified + SLR	No Scour	543 (2,415)	75 (334)	60 (81)
	4.7 (1.4)			

Table 36: Substructure Input Loads at Bent 13 on the Bridge to I-10 Eastbound at Exit 30

Storm Surge Scenario	Scour Depth Feet (Meters)[300]	Axial Tension Load kips (kN)	Lateral Load kips (kN)	Bending Moment Kip-Ft (kN-meter)
Hurricane Katrina Base Case	No Scour	543 (2,415)	239 (1,063)	282 (382)
	4.3 (1.3)			
Hurricane Katrina Shifted	No Scour	543 (2,415)	175 (778)	464 (629)
	5.0 (1.5)			
Hurricane Katrina Shifted + Intensified + SLR	No Scour	543 (2,415)	94 (418)	215 (292)
	5.0 (1.5)			

[299] The analysis was run with and without scour conditions.
[300] The analysis was run with and without scour conditions.

Table 37: Substructure Results at Bent 11 on the Bridge to I-10 Eastbound at Exit 30

Storm Surge Scenario	Scour Depth Feet (Meters)	Results from GROUP Analysis			Total Pile Soil Axial Tensile Resistance kips (kN)	Pile Soil Axial Tensile Resistance Sufficient?[301]	Pile Structural Axial Capacity Sufficient?[302]	Pile Structural Shear Capacity Sufficient?[303]	Pile Structural Bending Moment Capacity Sufficient?[304]
		Maximum Bending Moment Kip-Feet (kN-Meter)	Maximum Shear kips (kN)	Maximum Tension Load per Pile kips (kN)					
Hurricane Katrina Base Case	No Scour	1,142 (1,549)	63 (280)	200 (890)	232 (1,032)	Yes	Yes	No	No
	3.1 (0.9)	1,250 (1,695)	69 (307)	200 (890)	222 (988)	Yes	Yes	No	No
Hurricane Katrina Shifted	No Scour	792 (1,074)	45 (200)	193 (859)	232 (1,032)	Yes	Yes	Yes	No
	4.7 (1.4)	917 (1,243)	54 (240)	190 (845)	216 (961)	Yes	Yes	Yes	No
Hurricane Katrina Shifted + Intensified + SLR	No Scour	475 (644)	29 (129)	188 (836)	232 (1,032)	Yes	Yes	Yes	No
	4.7 (1.4)	563 (763)	36 (160)	188 (836)	216 (961)	Yes	Yes	Yes	No

301 Total pile tensile resistance is compared to maximum tension load per pile to determine if the soil can resist uplift forces acting on the pile without failure.
302 The concrete piles have a calculated structural tensile capacity of 386 kips (1,717 kilonewtons) in accordance to the *LRFD Bridge Design Specifications* document. This value is compared to the maximum tension load per pile to determine if the pile will break due to the tensile load.
303 The concrete piles have a calculated structural shear capacity of 55 kips (245 kilonewtons) in accordance to the *LRFD Bridge Design Specifications* document. This value is compared to the maximum shear load per pile to determine if the pile will break due to the shear load.
304 The concrete piles have a calculated structural bending moment capacity of 233 feet-kips (316 kilonewton-meters) in accordance to the *LRFD Bridge Design Specifications* document. This value is compared to the maximum bending moment load per pile to determine if the pile will break due to the shear load.

Table 38: Substructure Results at Bent 13 on the Bridge to I-10 Eastbound at Exit 30

Storm Surge Scenario	Scour Depth Feet (Meters)	Results from GROUP Analysis			Total Pile Soil Axial Tensile Resistance kips (kN)	Pile Soil Axial Tensile Resistance Sufficient?[305]	Pile Structural Axial Capacity Sufficient?[306]	Pile Structural Shear Capacity Sufficient?[307]	Pile Structural Bending Moment Capacity Sufficient?[308]
		Maximum Bending Moment Kip-Feet (kN-Meter)	Maximum Shear kips (kN)	Maximum Tension Load per Pile kips (kN)					
Hurricane Katrina Base Case	No Scour	958 (1,299)	54 (240)	100 (445)	242 (1,076)	Yes	Yes	Yes	No
	4.3 (1.3)	1,083 (1,469)	63 (280)	100 (445)	227 (1,010)	Yes	Yes	No	No
Hurricane Katrina Shifted	No Scour	708 (960)	40 (178)	90 (400)	242 (1,076)	Yes	Yes	Yes	No
	5.0 (1.5)	808 (1,096)	49 (218)	90 (400)	222 (988)	Yes	Yes	Yes	No
Hurricane Katrina Shifted + Intensified + SLR	No Scour	333 (452)	21 (93)	90 (400)	242 (1,076)	Yes	Yes	Yes	No
	5.0 (1.5)	417 (565)	27 (120)	90 (400)	222 (988)	Yes	Yes	Yes	No

[305] Total pile tensile resistance is compared to maximum tension load per pile to determine if the soil can resist uplift forces acting on the pile without failure.
[306] The concrete piles have a calculated structural tensile capacity of 386 kips (1,717 kilonewtons) in accordance to the *LRFD Bridge Design Specifications* document. This value is compared to the maximum tension load per pile to determine if the pile will break due to the tensile load.
[307] The concrete piles have a calculated structural shear capacity of 55 kips (245 kilonewtons) in accordance to the *2012 AASHTO LRFD Bridge Design Specifications* document. This value is compared to the maximum shear load per pile to determine if the pile will break due to the shear load.
[308] The concrete piles have a calculated structural bending moment capacity of 233 feet-kips (316 kilonewton-meters) in accordance to the *2012 AASHTO LRFD Bridge Design Specifications* document. This value is compared to the maximum bending moment load per pile to determine if the pile will break due to the shear load.

The results indicate the piles have sufficient axial capacity to resist the uplift force on the superstructure (up to the point the anchor bolts on the superstructure fail) under all three surge scenarios, but the piles are not able to resist the lateral forces (shear and moment) under any of the scenarios and may fail due to shear and / or bending. However, during Hurricane Katrina, the storm surge only caused superstructure damage and did not damage the piles. The discrepancy between the modeled results and what actually occurred can likely be attributed to the lack of detailed geotechnical data, such as the shear strength parameters and physical properties (e.g., plasticity characteristics, unit weight) of soils, in the vicinity. A full analysis, beyond the scope of this study, should involve development of the shear strength parameters and the physical properties of the soils based on soil borings with SPT and / or cone penetration test soundings along with geotechnical laboratory tests on collected soils samples during investigation.

Step 6 – Identify Adaptation Option(s)

Under all three scenarios, Step 5 indicated that adaptation options are required for dealing with the potential of deck uplift and float away (Failure Mode One) and also for dealing with the excessive lateral forces on the piles (Failure Mode Two), actual performance during Hurricane Katrina notwithstanding. No separate adaptation options are required under any of the scenarios to deal with scour (Failure Mode Three).

Viable adaptive design options that would attempt to prevent Failure Modes One or Two from occurring include:

- One of the adaptation options recommended in *Guide Specification for Bridges Vulnerable to Coastal Storms* is to design the superstructure to break away from the substructure in a significant storm surge. While, the designers of the case study bridge did not intend the superstructure to breakaway in a significant storm surge, this is what occurred in Katrina. A breakaway superstructure would allow for a much shorter and less expensive rebuild period than if the substructure was allowed to be damaged. In essence, the facility is designed for a controlled failure if surge and wave forces become too great. This is an important adaptation concept that might be worth considering for similar types of bridges in comparable environments.
- Design the anchor bolts and horizontal through girder bolts to fail at a lower load level resulting in lower loads transmitted to the piles in a significant storm surge. Although the bolts would fail at a lower level and alleviate some of the shear and bending stresses on the piles, more spans could breakaway when compared to the current bolt configuration.
- Improve the connection between the superstructure and substructure and also investigate if the substructure foundations require strengthening after obtaining all geotechnical information
- Investigate the use or partial use of installing open grid decks to possibly reduce the vertical loads imposed by a storm surge. Note that this would also help prevent damage from uplift and may be able to be used in lieu of the severability approach whereby the deck is designed to float off if uplift forces are too strong. Open grid decks are lighter and would reduce the vertical forces imposed on the superstructure, but may have corrosion problems. Open grid

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decks also sometimes develop cracks (fatigue and stress) and have much higher maintenance needs than concrete decks.

- In order to lower the magnitude of the lateral wave forces, one might consider replacement of the girders with others having a shallower section and/or replace the parapets with a more open railing system. A shallower girder can be installed by adding more girders or replacing with a slab type system, but this might prove costly. Replacing a parapet with a more open railing system may not follow standards that are typically used for such ramps. Benefits and disadvantages would need to be evaluated.
- Redesign the superstructure to have removable deck sections for portions of the bridge which are closer to water level. Sufficient advance notice of an upcoming storm surge is needed for this repair option to be successful especially given the time needed to remove the sections and possible high winds associated with an expected storm. The girders can also be removable but would add to the length of advance notice time needed to have them removed.
- Replace the bridge with a raised/protected embankment section up to a point high enough along the ramp where a bridge section can be used.
- Investigate eliminating the entire ramp and interchange after the next major storm causes severe damage. Discussions with stakeholders would be needed before this decision could be made.

Step 7 – Assess Performance of the Adaptation Option(s)

In this step, the performance of each adaptive design option mentioned in Step 6 would be determined under each of the storm surge scenarios. This would aid in the development of effective adaptation solutions and serve as a basis for a benefit-cost analysis. This step was not completed for this particular case study due to resource limitations.

Step 8 – Conduct an Economic Analysis

An economic analysis was not included in this case study but is recommended for facility-level adaptation assessments. See Section 4.4.1 for an example of how an economic analysis was applied to a culvert exposed to changes in precipitation due to climate change.

Step 9 – Evaluate Additional Decision-Making Considerations

Additional factors that will influence decision-making on what adaptation option to consider include:

- How much a significant storm surge or future sea level rise would affect the land uses served by the ramp. It is conceivable that the next significant storm surge could significantly damage the superstructure and substructure of the ramp and may also eliminate the land uses served by the ramp. If those land uses are not re-built, the need for the ramp may be lessened to the point that it is no longer needed and expensive reconstructions or adaptations are not necessary. Elimination of the interchange may also bring up the planning question of whether or not to increase the capacity of I-10. An important concept in transportation adaptation planning is that transportation facilities should not be adapted beyond the viability of the land uses they serve. Public meetings with nearby property owners would need to be held to discuss this issue.

- The public acceptance of an open-bridge deck or more open parapet walls and possible increased safety hazards from both adaptation options.

Step 10 – Select a Course of Action

The course of action recommended for this case study is the eventual elimination of all or a portion of the Exit 30 interchange the next time a storm causes major damage to the facility. The near-term course of action should be a detailed study exploring the implications of this option. The study should include an economic analysis of maintaining the interchange versus closing it down. The issues of how the closure would affect volume of traffic on I-10 (dependent on how much of the interchange is to be demolished) should be made a part of the study.

Step 11 – Plan and Conduct Ongoing Activities

Specific ongoing activities will depend upon the adaptation option selected. Generally, ongoing adaptation options for a coastal bridge would include monitoring the performance of the adaptive actions during future storm events and documentation of instances when the adaptation might have saved money from what would have happened had the current design remained in place.

Conclusions

This case study has, using the *General Process for Transportation Facility Adaptation Assessments*, demonstrated how a bridge can be analyzed for potential storm surge scenarios, including those where sea level rise has been factored in. Both the deck and the substructure of the portion of the ramp being studied were found to be vulnerable to each of the three surge scenarios tested. To address these vulnerabilities, several adaptation options were presented for consideration. Also, the overall area was considered and the adaptive option of eliminating the interchange was presented.

The two important lessons learned in this case study are that (1) the worst case storm surge scenario does not necessarily translate to the worst effect on the facility and that (2) one should examine the overall viability of a facility as part of an adaptation assessment and consider elimination / retreat as an adaptive option in some situations.

4.4.6 Road Alignment Exposure to Storm Surge – I-10 (Mileposts 24 to 25)

Introduction

Stronger storms and higher sea levels increase the risk of water surging over the paved surface of coastal highways. Known as overtopping, such an event due to storm surge can cause a variety of impacts to road and rail alignments located along coastlines. This chapter illustrates how the *General Process for Transportation Facility Adaptation Assessments* can be used to analyze the potential risks of this happening on I-10 on the south side of Mobile (between mileposts 24 and 25). The assessment determines the potential for roadway overtopping, the risk of roadway embankment failure, the degree of inland flooding caused by potential storm surge scenarios, and the implications of flow velocities through bridge underpasses.

It was found that all of the storm surge scenarios tested present some threat of inundation and erosion to the roads and railroad passing through the underpasses in the study corridor. Two of the three surge scenarios tested overtop I-10 and one of them causes enough erosion to fully breach the highway embankment. An adaptation option is recommended that armors the I-10 embankment at its low spot and hardens the road and rail infrastructure passing through the underpasses.

> **Case Study Highlights**
>
> **Purpose:** To evaluate the potential for roadway overtopping, embankment failure, and inland flooding, and determine the implications of flow velocities through bridge underpasses due to storm surge.
>
> **Approach:** The potential for overtopping was evaluated by overlaying the projected surge flood elevations onto the roadway profile and cross-sections of the underpasses. Failure (breaching) of the roadway was evaluated by modeling the road as a barrier across the flow, then calculating erosion potential and erosion rates based on estimated flow rates. The potential and degree of inland flooding of the nearby Oakdale neighborhood was determined using a time-step analysis and the storm surge hydrographs. Then, the maximum flow velocities through bridge underpasses were estimated using a FHWA tidal hydraulics orifice approach combined with the time-step analysis of the storm surges.
>
> **Findings:** The segment analyzed have the potential to overtop and be vulnerable to erosion under certain storm scenarios.
>
> **Viable Adaptation Options:**
>
> - Harden underpasses
> - Armor roadway embankment
> - Raise the roadway
>
> **Other Conclusions:** There has been limited research on methods for predicting roadway breaches.

Application of the General Process for Transportation Facility Adaptation Assessments

Step 1 – Describe the Site Context

I-10 is a cross-country highway that runs through eight states connecting Los Angeles, CA to Jacksonville, FL. In Alabama, I-10 traverses Mobile and Baldwin Counties and is a critical route for traffic crossing Mobile Bay and accessing downtown Mobile from the south and west. The study segment is located approximately one mile south of downtown Mobile (see Figure 73). In this segment, I-10 is a 10-lane freeway running parallel to Garrows Bend, an estuary within Mobile Bay that bounds the west side of McDuffie Island. Garrows Bend is well connected to Mobile Bay and is thus expected to experience storm surge flooding equivalent to that

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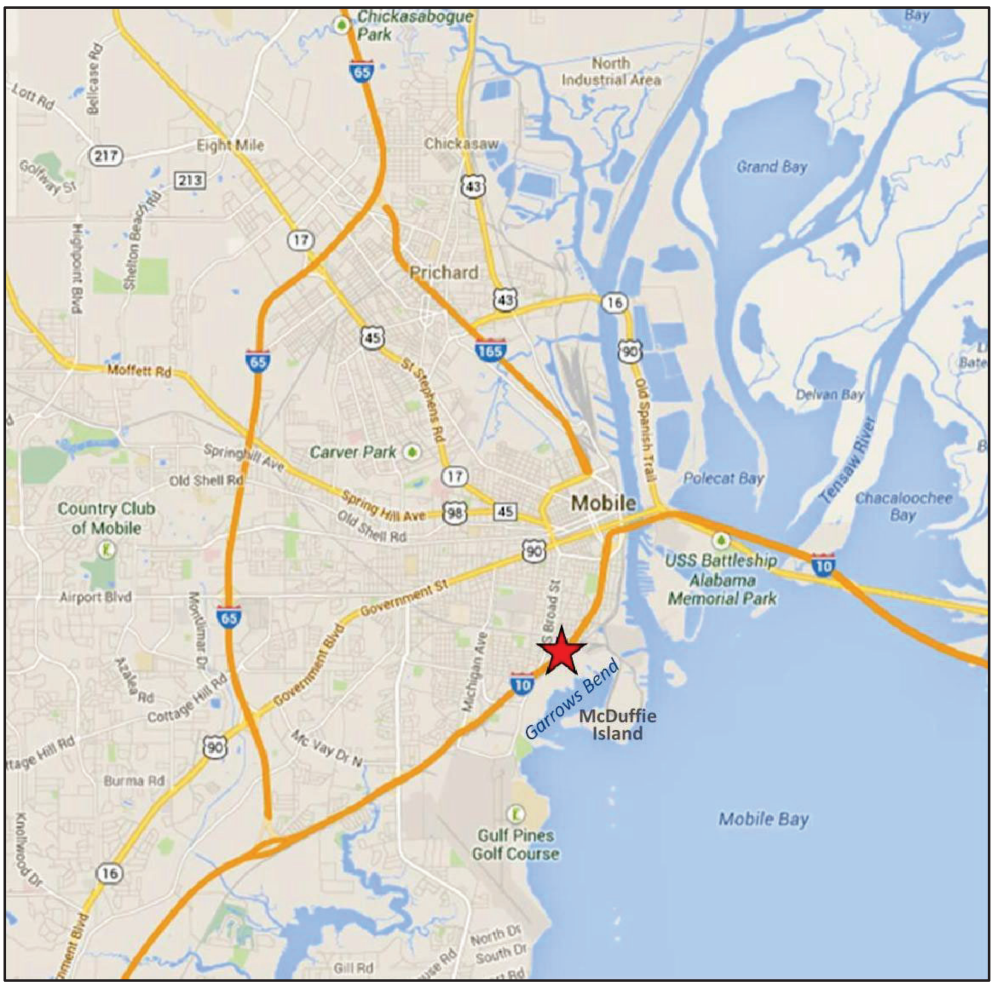
experienced in Mobile Bay. I-10 is offset approximately 1,000 to 2,000 feet (305 to 610 meters) from the shoreline of Garrows Bend. Surrounding land uses include the residential neighborhood of Oakdale to the north and west of the road and industrial facilities located to the east, between the roadway and the shoreline. I-10 is owned and maintained by ALDOT.

Step 2 – Describe the Existing Facility

The study segment lies between mileposts 24 and 25, between the Broad Street and Warren Street bridges (see Figure 74). A third bridge crossing lies on the northern end of the study segment where I-10 crosses Tennessee Street and a railroad line. A stream is piped underneath the roadway embankment near this crossing.

The study segment is approximately 4,300 feet (1,311 meters) in length and 170 feet (52 meters) wide with 10 travel lanes and four shoulders. Each travel lane is 11 to 12 feet (3.4 to 3.7 meters) wide and each shoulder is 12 to 14 feet (3.7 to 4.3 meters) wide.

Figure 73: Location of the I-10 Study Segment in Relation to Mobile Bay and the Mobile Metropolitan Area[309]

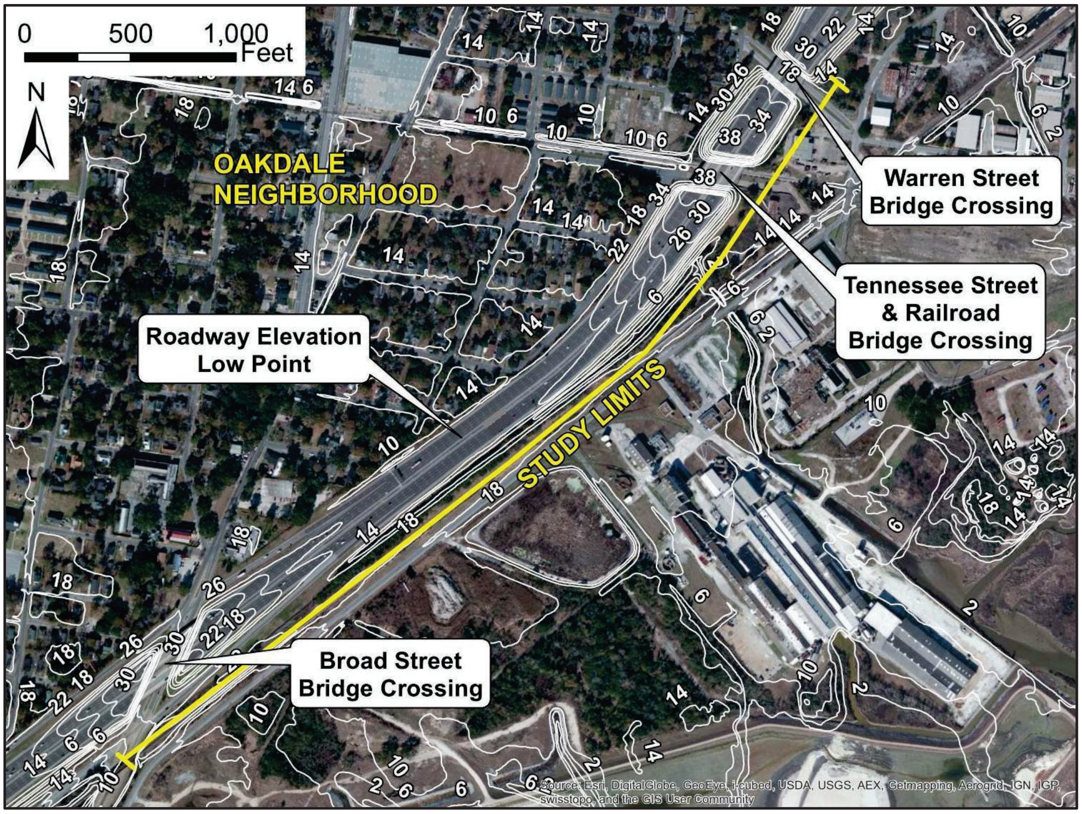


The roadway profile has a low point at the center of the study segment, midway between the Tennessee Street and Broad Street crossings. This low point has an elevation of 14.6 feet (4.5 meters),[310] whereas the bridges at Broad Street and Tennessee Street are at the highest points along the segment with elevations of 34 feet (10.4 meters) and 40 feet (12.2 meters), respectively. Table 39 summarizes the bridge and underpass dimensions at the three crossings. All dimensions described are measured using two-foot (0.6 meter) contour data maintained by the City of Mobile and GIS analysis of aerial imagery; an adaptation analysis for an actual project would require site surveys to gather more accurate information.

[310] All elevations reported in this case study are in relation to the North American Vertical Datum 1988 (NAVD88).

Figure 75 shows ground level views of the roadway and the three underpasses.

Figure 74: Plan View of I-10 Showing Study Limits, Bridge Crossings, and Elevation Contours[311]



[311] The contour elevations shown in this map do not include the elevations on the bridge overpasses.

Table 39: Dimensions of the Bridge Underpasses along the I-10 Study Segment[312]

	Broad Street Crossing Feet (Meters)	Tennessee Street and Railroad Crossing Feet (Meters)	Warren Street Crossing Feet (Meters)
I-10 Bridge Top Elevation	34.0 (10.4)	40.0 (12.2)	30.0 (9.1)
Road / Railroad Elevation Under the Bridge	12.6 (3.8)	11.6 (3.5)	13.1 (4.0)
Road / Railroad Width Under the Bridge	78 (23.8)	94 (28.7)	92 (28.0)
Estimated Vertical Clearance Above Road / Railroad[313]	16.4 (5.0)	23.4 (7.1)	11.9 (3.6)

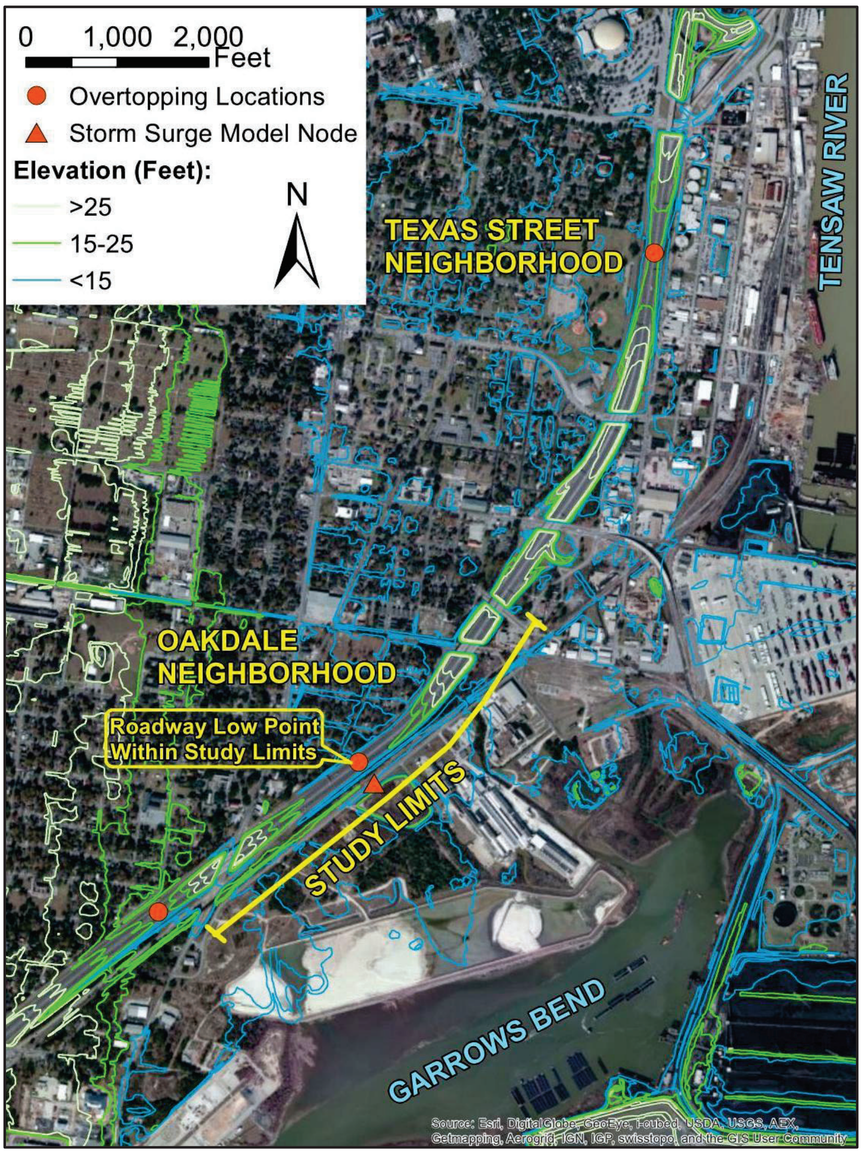
[312] Note: All elevations in this study are in relation to the North American Vertical Datum of 1988 (NAVD88).
[313] Assumes a five foot (1.5 meter) depth between the top of deck and the bottom of girders.

Figure 75: Study Area Images
(Top to Bottom: I-10 Roadway Looking East from North of the Embankment Near the Low Point, Broad St. Underpass, Tennessee St. and Railroad Underpass, and Warren St. Underpass Looking North)[314]

[314] Source: Google Maps Street View

The study limits for this assessment were chosen to analyze the effects of storm surge overtopping at a well-defined low point in the roadway and storm surge flooding impacts through the bridge underpass pathways. The low-lying areas that are vulnerable to flooding continue northward as shown in Figure 76 and it is expected that similar storm surge flooding dynamics will occur along the length of I-10 in these areas. However, to provide an example assessment, this case study was limited to the one roadway low point near the Oakdale neighborhood and nearby crossings; a flooding analysis for that neighborhood was also undertaken. In a typical analysis of storm surge impacts on road and rail alignments, one might instead set the assessment limits based on the entire affected segment.

Figure 76: Topography in the Vicinity of the I-10 Study Segment



Step 3 – Identify Climate Stressors That May Impact Infrastructure Components

For this roadway segment, storm surge and the resulting flooding are the primary climate change-related environmental factors likely to affect the roadway. In addition, this assessment also considered sea level rise as an added factor in the most extreme storm surge scenario analyzed.

Additional related roadway components not considered in this assessment that might be impacted by changing climatic conditions include the roadway pavement drainage system, culvert / storm sewer system, embankment slope protection, and roadway sub-base. Roadway pavement drainage could be impacted by increased precipitation intensity where the flat slope of a roadway may not meet the design spread conditions for a given storm event because of its location. The culvert / storm sewer system could also be impacted by changing tailwater[315] conditions caused by sea level rise. Increased tailwater will decrease the ability of the system to handle water flows. Embankment slope protection for the roadway could be at risk if sea levels or riverine floodplain conditions were to rise and expose the approach roadway to erosive flow conditions. Lastly, the roadway sub-base could become compromised if sea level rise were to result in permanent inundation of the roadway sub-base. Inundation of the sub-base would result in a loss of bearing strength and potentially cause hydraulic forcing of voids in the base itself that were originally caused from repeated loading / unloading of the roadway from normal traffic.

Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes

The following three storm surge scenarios were considered for this adaptation assessment:

- **Hurricane Katrina Base Case Scenario**: This scenario represents the surge conditions that actually occurred in Mobile with Hurricane Katrina making landfall at the Louisiana-Mississippi border. The effects of Hurricane Katrina on the Mobile area were not as severe as they were at the Louisiana-Mississippi border.
- **Hurricane Katrina Shifted Scenario**: This scenario estimates the surge levels that would occur if Hurricane Katrina's path was shifted east to make landfall in Mobile.
- **Hurricane Katrina Shifted + Intensified + Sea Level Rise (SLR) Scenario**: This scenario estimates the surge levels that would occur if Hurricane Katrina was shifted, intensified with stronger winds due to climate change, and came on top of 2.5 feet (0.8 meters) of sea level rise.

A more detailed description of each scenario and how it was developed can be found in Section 4.4.4 of this document (under Step 4) and in the *Climate Variability and Change in Mobile, Alabama* report.[316]

For this case study, site-specific flood elevations under each scenario were calculated for a point located along the I-10 roadway study segment, approximately 290 feet (88 meters) southeast of

[315] Tailwater refers to the water at a system (e.g., culvert) outlet.
[316] USDOT, 2012

the roadway low point. This point, shown in Figure 76 as the storm surge model node, is the node for which flooding elevations were calculated as part of the ADvanced CIRCulation (ADCIRC) storm surge modeling and was chosen to be representative of flood elevations for the study site. The three storm surge elevations for each surge scenario (calculated at the storm surge model node location) and the current FEMA 100-year flood elevation for the study site location are summarized in Table 40.

Table 40: Flood Elevations for the Storm Surge Scenarios and the Current FEMA 100-Year Flood at the Storm Surge Model Node near the I-10 Study Segment[317]

	FEMA 100-year Flood Feet (Meters)[318]	Hurricane Katrina Base Case Scenario Feet (Meters)	Hurricane Katrina Shifted Scenario Feet (Meters)	Hurricane Katrina Shifted + Intensified + SLR Scenario Feet (Meters)
Storm Surge / Flood Elevation	11.8 (3.6)	13.0 (4.0)	20.3 (6.2)	25.0 (7.6)

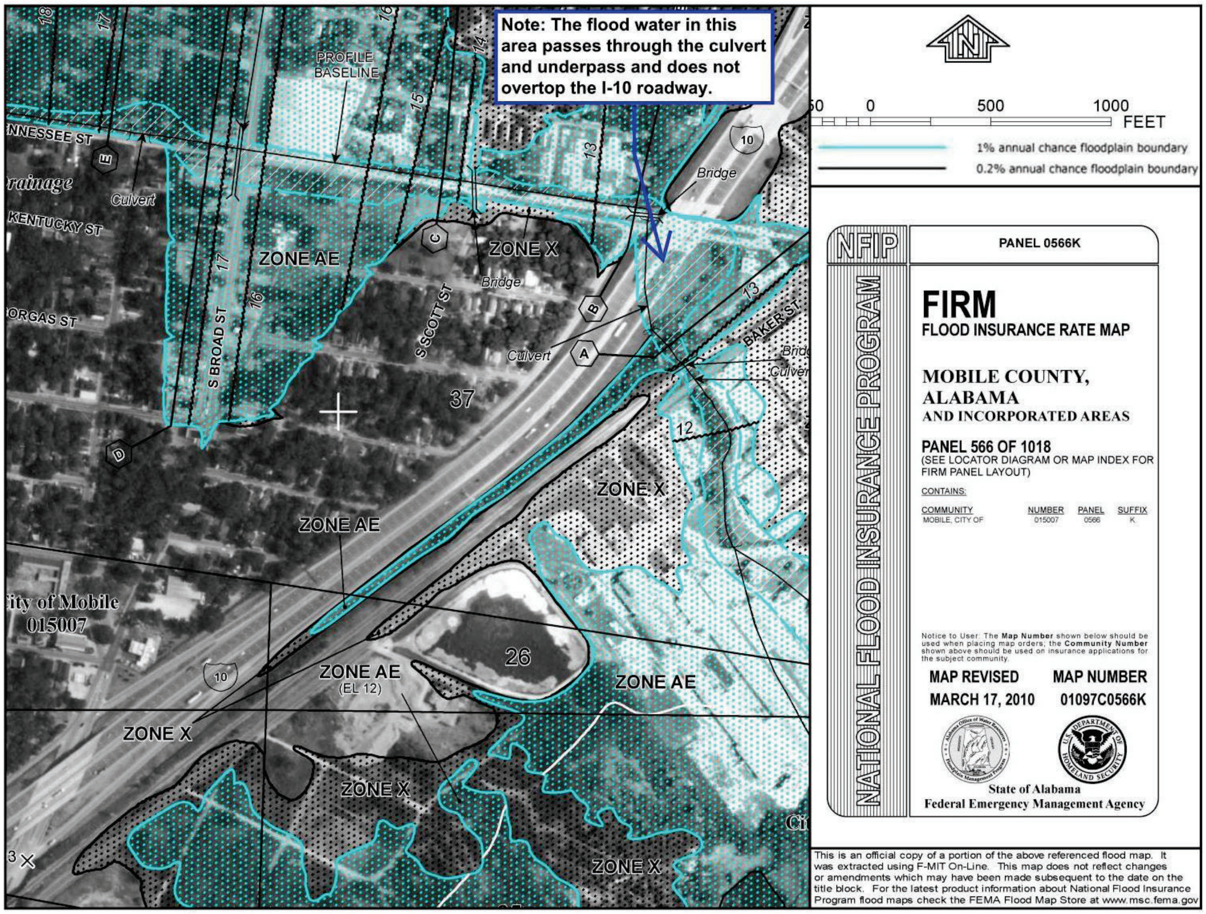
According to the FEMA flood insurance study of Mobile County, Alabama, the 100-year flood elevation due to coastal flooding in the vicinity of the study site is 11.8 feet (3.6 meters).[319] Comparing this to the predicted storm surge elevations, all three storm surge scenarios produce floods with return periods in excess of the current 100-year event. Figure 77 shows the FEMA 100-year flood boundary based on the flood insurance study. Note that the extent of flooding shown in the FEMA flood map includes both tidal and riverine flooding sources. Potential riverine flooding of the stream channel along Tennessee Street causes the flood elevations along this channel to be higher moving further inland. As evident in Figure 77, the flood elevation along Tennessee Street near its intersection with South Broad Street is almost 17 feet (5.2 meters); a value much higher than the coastal flooding elevation of 11.8 feet (3.6 meters). This suggests that the potential increased impacts due to riverine flooding, in addition to coastal flooding, may need to be considered in areas near rivers or streams. Such an effort was beyond the scope of this case study but should be considered if actual adaptation work were to be done in the area.

Analysis of historical flooding events provides background insight into the local impacts resulting from past climate events. During Hurricane Katrina, flood elevations of up to 11.5 feet (3.5 meters) were reported at the Mobile State Docks, located approximately three miles (4.8 kilometers) north of the study site.[320] This actual flood elevation is less than the storm surge flood elevation of 13 feet (4 meters) predicted in the Hurricane Katrina Base Case Scenario

[317] Note: The storm surge elevations shown here include wave run-up effects.
[318] See the Mobile County Flood Insurance Study (FEMA, 2010d)
[319] The FEMA 100-year flood elevation of 11.8 feet was obtained from the Mobile County Flood Insurance Study (FEMA, 2010d) documentation of stillwater elevations based on coastal transects. This study site is located along the coastline between the Hannon Road and US 90.
[320] NOAA, 2013d

model. However, information regarding actual flood elevations at the study site during Hurricane Katrina is limited. Flood elevations at the study site may differ from the State Docks value due to its location relative to Mobile Bay and wave run-up effects. The FEMA flood insurance study also cites a number of significant historical storms that have caused severe flooding in Mobile. Of note are Hurricane Camille of 1969 that produced a recorded peak tide of 7.4 feet (2.3 meters) in Mobile, and a 1926 hurricane that produced tides of 10.9 feet (3.3 meters) above normal tide in Mobile.[321]

Figure 77: FEMA Flood Insurance Rate Map in the Vicinity of the I-10 Study Segment [322]



Step 5 – Assess Performance of the Existing Facility

Four potential impacts of storm surge flooding were evaluated to assess the performance of the existing roadway under each of the potential storm surge scenarios. These include:

- Storm surge overtopping of the I-10 roadway and underpasses

[321] FEMA, 2010d
[322]Source: FEMA, 2010e (as modified). Note: The elevations shown are in NAVD88.

- I-10 roadway embankment breaching due to overtopping flows
- Inland flooding impacts to the Oakdale neighborhood in terms of total flood volume entering the neighborhood and time to drain during the ebb of the surge
- Implications of flow velocities through the underpasses at the three bridge crossings.

Each of these impacts is discussed in the sub-sections that follow.

Storm Surge Overtopping of I-10 Roadway and Underpasses

The degree of overtopping of the I-10 roadway and underpasses was evaluated by overlaying the predicted storm surge flood elevations onto the roadway profile and cross-sections of the underpasses (see Figure 78). The profile and cross-section elevations were produced using AutoCAD Civil 3D with two foot (0.6 meter) planimetric contour data maintained by the City of Mobile. The brown lines in the figure represent the highest ridge along the roadway and the underpasses, while the blue dashed lines represent the highest flood level that is reached in each of the three storm surge scenarios.

As shown in Figure 78, only the Tennessee Street and Railroad Underpass location is expected to experience flooding under the Hurricane Katrina Base Case Scenario. Although the Broad Street underpass is also located at a slightly lower elevation than the Hurricane Katrina Base Case Scenario flood elevation, there are no overland flow paths into this underpass from the seaside direction for flood elevations lower than approximately 14 feet (4.3 meters), and thus flooding is not expected on this segment of Broad Street for this scenario.

Figure 78 also shows that the Hurricane Katrina Shifted Scenario and the Hurricane Katrina Shifted + Intensified + SLR Scenario will cause overtopping of the I-10 roadway and flooding of all three underpasses. Based on the flood elevations, the sequence of flooding under both of these scenarios proceeds as follows: first the Tennessee Street and Railroad Underpass is flooded, followed by the Warren Street underpass, and then the Broad Street underpass and I-10 roadway at around the same time.

It is important to evaluate whether the existing roadway is currently meeting design standards for roadway flooding. Although ALDOT does not indicate a specific return period storm for design of roadways against flooding, the Code of Federal Regulations states that the design flood for through lanes of interstate highways is the 50-year flood.[323] The FEMA 50-year flood elevation in the vicinity of the study site is 10.6 feet (3.2 meters).[324] As discussed earlier, the FEMA 100-year flood elevation is 11.8 feet (3.6 meters), which does not overtop the I-10 roadway study segment as shown in Figure 77. Therefore, the I-10 study segment is currently meeting the federal design requirement as well as accommodating the 100-year storm event.

[323] USDOT, 1994.
[324] FEMA, 2010d

Figure 78: Elevation Views of the I-10 Study Segment Roadway Profile and Underpass Cross-Sections

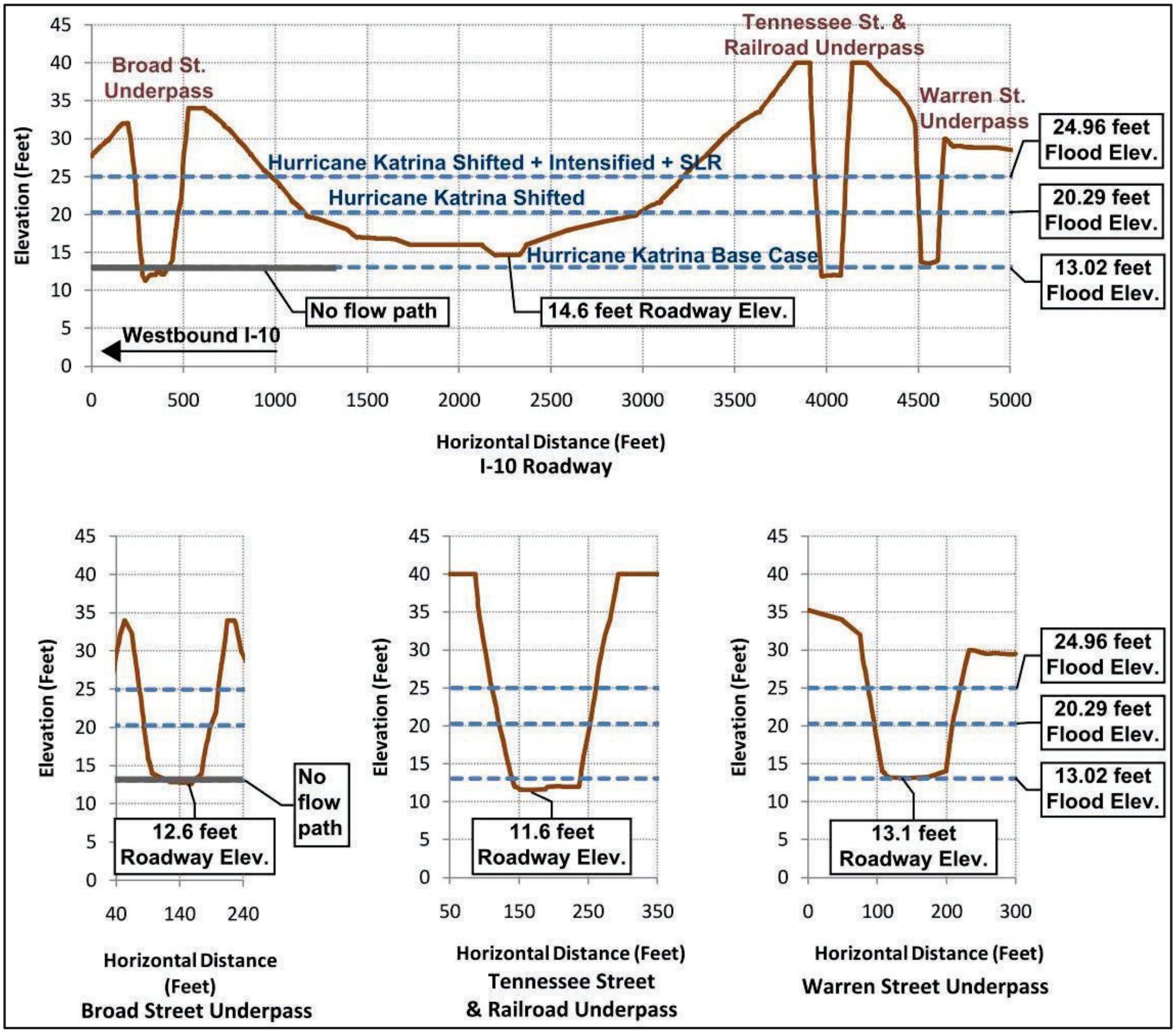


Figure 79, Figure 80, and Figure 81 show potential inundation zones under each of the storm surge scenarios. Comparing these figures to the FEMA 100-year flood map (Figure 77), it appears that the flooding extent predicted for the Hurricane Katrina Base Case Scenario storm surge is comparable to that of the 100-year storm, whereas the Hurricane Katrina Shifted Scenario and the Hurricane Katrina Shifted + Intensified + SLR Scenario have much larger impact areas.

Figure 79: Hurricane Katrina Base Case Scenario Flood Zone in the Vicinity of the I-10 Study Segment, Flood Elevation 13 Feet (Four Meters)

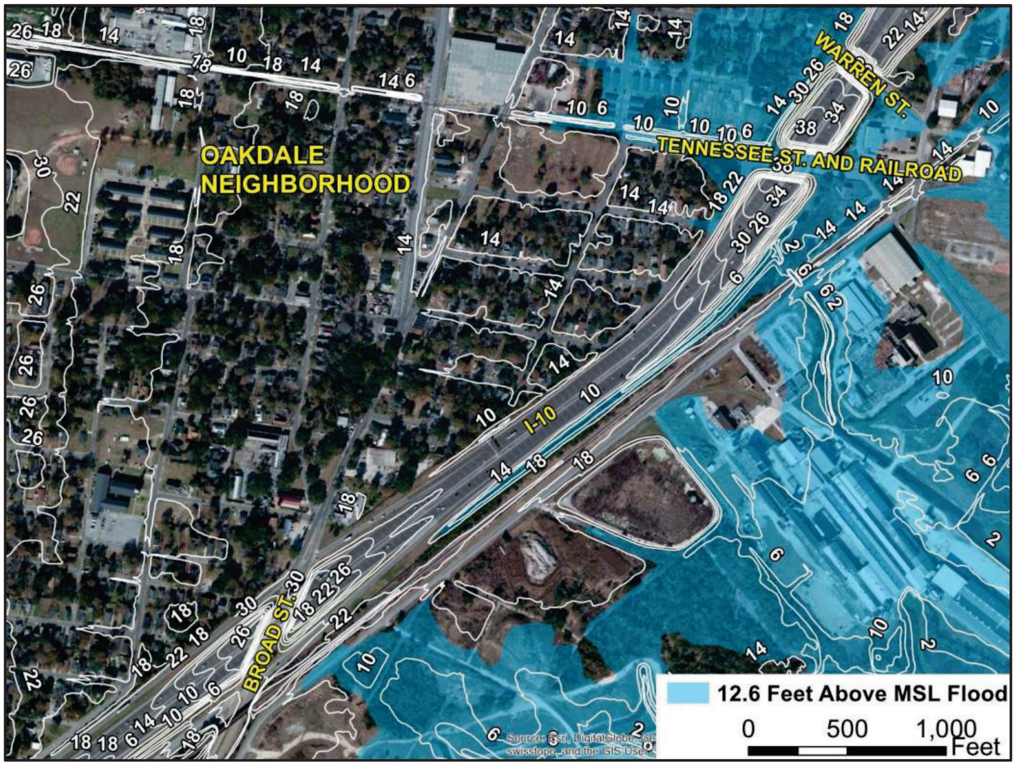


Figure 80: Hurricane Katrina Shifted Scenario Flood Zone in the Vicinity of the I-10 Study Segment, Flood Elevation 20.3 Feet (6.2 Meters)

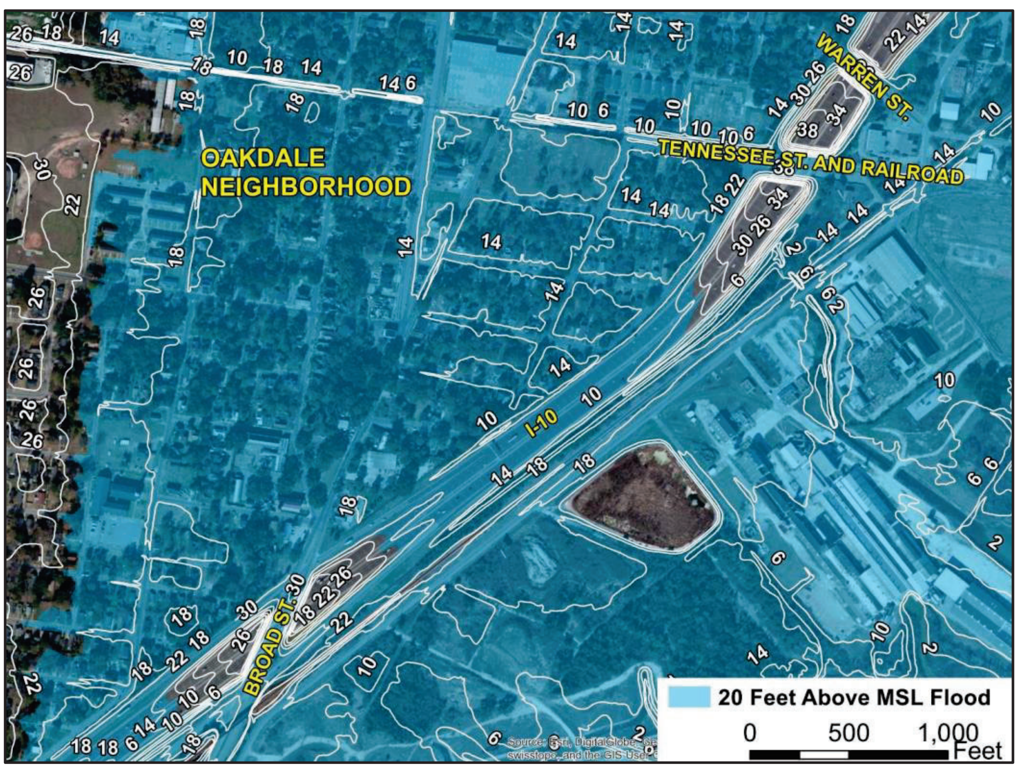
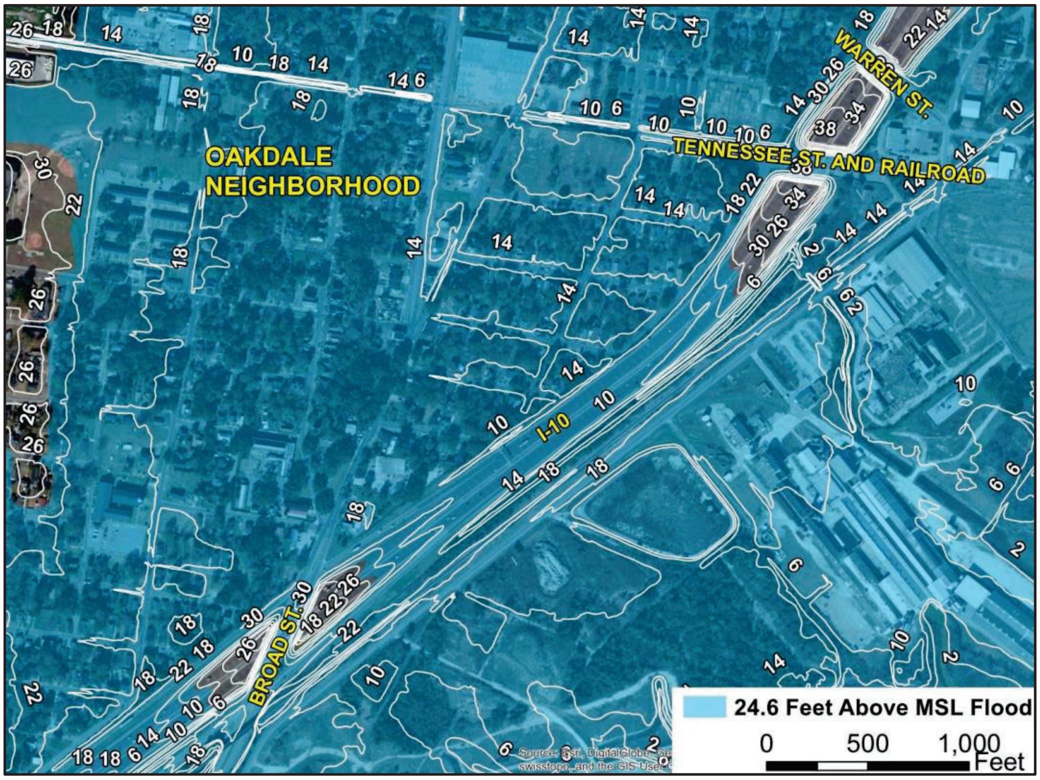


Figure 81: Hurricane Katrina Shifted + Intensified+ SLR Flood Zone in the Vicinity of the I-10 Study Segment, Flood Elevation 25 Feet (7.6 Meters)



I-10 Roadway Embankment Breaching

The most common type of embankment failure during flooding is erosion of the embankment due to overtopping.[325] Erosion will occur if erosive forces created by high flow velocities over the embankment exceed the ability (that is, strength) of the embankment to resist erosion. Erosion can begin at the break point between the downstream shoulder and earthen slope and progress toward the roadway and down the slope. Alternatively, erosion can also begin at the toe (base) of the downstream slope, typically under low tailwater[326] elevation conditions. For embankments consisting of non-cohesive materials such as sand, breaching typically occurs as progressive surface erosion.[327] For embankments composed of cohesive materials such as clay, the erosion typically begins as rills[328] which start a headcutting[329] process that causes erosion to progress toward the crest of the embankment.[330]

[325] Chen and Anderson, 1986
[326] Tailwater elevation in this case refers to the water surface elevation on the downstream side of the embankment. This can also be described as the flood elevation inland of the roadway during surge flow and the flood elevation seaside of the roadway during ebb flow.
[327] Progressive surface erosion is the gradual erosion of soil particles as they are washed away by moving water.
[328] Rills are narrow channels that form in the surface of the embankment as flows begin to erode the embankment soil.
[329] Headcutting is a channel erosion process where erosion downcutting of the channel bed starts at the low point of the channel and progresses upstream / up-hill.
[330] ASCE EWRI, 2011

As noted above, the Hurricane Katrina Base Case Scenario is not expected to overtop the I-10 roadway, so no embankment erosion is expected with this scenario. Thus, the embankment erosion analysis was only performed for the Hurricane Katrina Shifted Scenario and the Hurricane Katrina Shifted + Intensified + SLR Scenario.

A key prerequisite to modeling the amount of erosion and the potential for breaching of the roadway is understanding the flow rates over the embankment. Because flow rates vary over the duration of a storm, a time-step analysis was performed at half-hour increments for each of the storm surge flooding scenarios. First, storm surge hydrographs for each scenario were developed to determine the flood elevation at varying time steps (see Figure 82). Next, stage[331]-discharge curves were developed to capture varying flow area geometries and head differentials[332] across the roadway at varying flood elevations. The stage-discharge curves were developed by calculating the discharge at various flood elevations to create a relationship between flood elevation and flow rate.

To calculate the discharges over the roadway, the roadway was modeled as a broad-crested weir[333] using the following formula:

$$Q_f = C\, bH^{3/2}$$

Where,

Q_f = The flow rate over the roadway (cubic feet per second)

b = Width of the submerged portion of the roadway (feet)

H = Hydraulic depth[334] (feet)

C = Discharge coefficient that accounts for the effects of contraction, velocity, and fluid properties (3.1 [English units] is used in this study assuming a rounded upstream edge due to the gradually sloped embankment and shoulder lane)

Topographic data showed that the roadway has a relatively low embankment at the low point. The height of the lowest point of the roadway embankment is no greater than three to four feet (0.9 to 1.2 meters) higher than the lowest ground elevation in the neighborhood. It was found after a time-step analysis of the storm surges, that the tailwater elevation rises rapidly during the surge and the roadway reaches submerged weir conditions[335] quickly. From this point on, the

[331] Stage refers to water elevation.
[332] Head differential is the difference between the storm surge flood elevation and the inland flood elevation above the top of the roadway.
[333] A weir is a barrier across a river (smaller than a dam) characterized by the allowance of water to flow over the top of the barrier. The broad-crested weir formula is a simplified approach to modeling the roadway embankment which assumes a rectangular cross-sectional flow area. To ensure that correct flow areas are used, in this study the hydraulic depth (see next footnote) is used as “H” in the equation that follows.
[334] Hydraulic depth is equivalent to the flow area divided by the width of the submerged section of roadway (“b” in the equation). The weir equation typically uses the difference between the water elevation and the weir crest as “H” in the equation, but using the hydraulic depth ensures that the correct flow areas are accounted for.
[335] Weir hydraulics is based on a condition of rapidly changing flow with fast flow conditions over the weir. Submergence occurs when the speed of the flow is limited by high tailwater depths.

roadway was modeled as a submerged weir using the following formula to calculate discharges over the roadway:

$$Q_s = Q_f \left[1 - \left(\frac{H_2}{H_1} \right)^{1.5} \right]^{0.385}$$

Where,

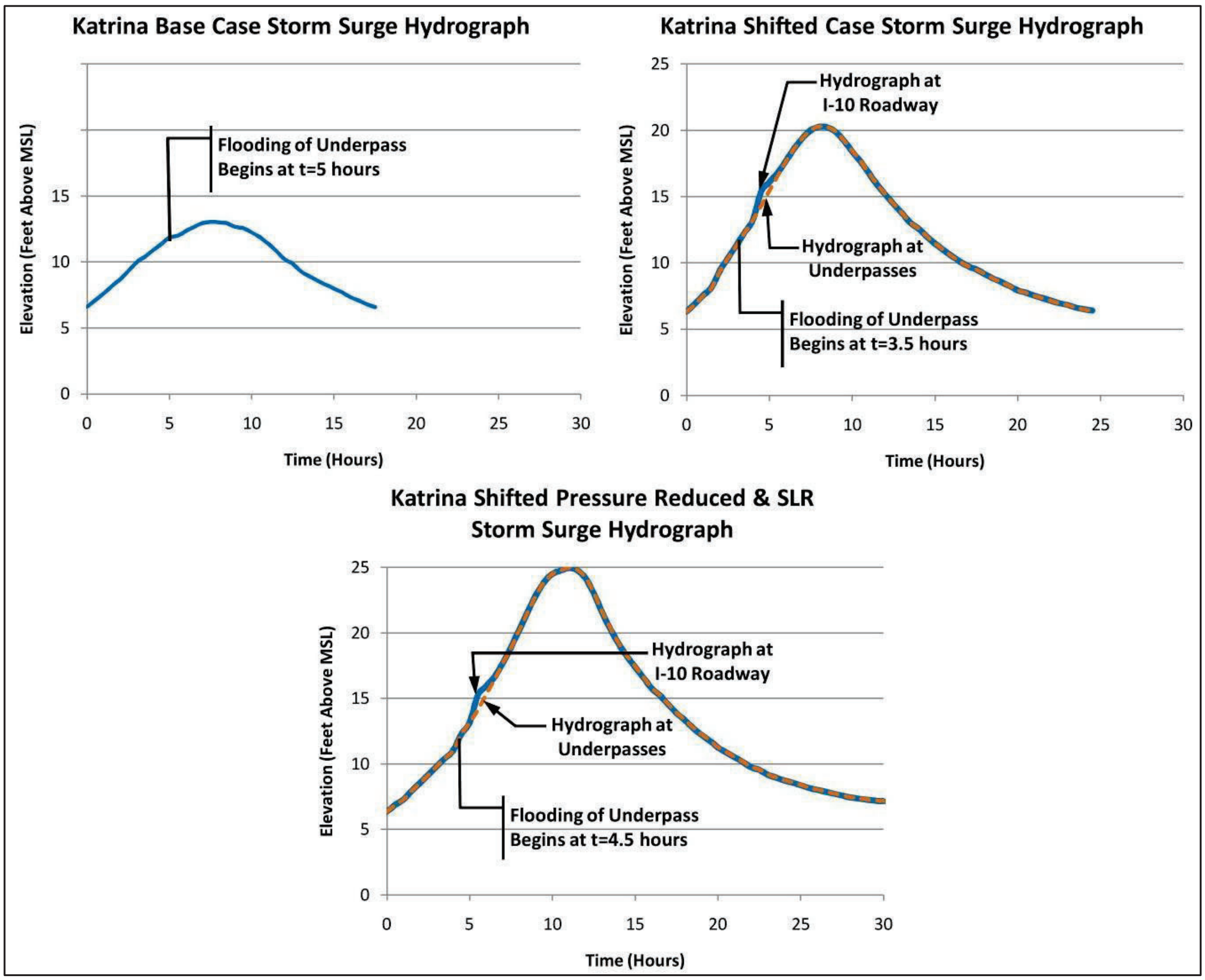
Q_s = Submerged weir flow rate (cubic feet per second)

Q_f = Unsubmerged weir flow rate (from previous formula, cubic feet per second)

H_1 = The upstream head elevation[336] above the crest (feet)

H_2 = The downstream head elevation above the crest (feet)

Figure 82: Storm Surge Hydrographs for the I-10 Study Segment



[336] Head elevation refers to the difference between the water surface elevation and the weir crest (top of weir) elevation.

Given the calculated flow rates over the embankment, the next step was to calculate erosion potential and erosion rate. Various models have been developed to predict the erosion potential of embankments. Many of these studies have aimed to correlate peak flow rates to hydraulic parameters for breached dams where the flow rate depends on the dimensions of the breached section. In this case, however, the flow rates are tied to storm surge flood elevations, which increase independently of the breach dimensions. As such, the embankment breaching analysis for this case study was conducted in two parts: first, a determination was made as to whether embankment erosion will begin based on permissible velocities and shear stresses[337] and, if so, an estimate of the erosion rate was made assuming breaching had begun.

The potential for erosion to begin on the embankment was evaluated based on the permissible shear stress of the materials comprising the embankment. For this study site, design plans showed that the embankment subgrade along this reach of I-10 was composed of loamy borrow material. Silt loam was therefore used for this analysis. However, if one were conducting an actual project, the soil type would need to be verified through field surveys for a more accurate estimation of erosion potential.

The threshold velocity and shear stress for erosion were determined through use of the critical velocity and critical shear stress of the soil, respectively. A critical velocity of two feet per second (0.6 meters per second) and a critical shear stress of 0.1 pounds per square foot (2.4 pascals), applicable to silt loam, were used in the analysis.[338] Aerial imagery shows that the embankment also contains vegetative growth, which appears to be short grass on both slopes,[339] but that bare patches of soil may also be present. Because erosion can initiate at weak points along the embankment slope, the values for soil were used instead of the higher permissible values provided by vegetation. If the shear stress caused by the flows overtopping the embankment exceeded the permissible shear stress, erosion would begin. The level of shear stress that determines if erosion will occur was calculated from the flow velocity according to the following formula:[340]

$$\tau = \frac{1}{8} f \rho V^2$$

Where,

τ = Shear stress (pounds per square foot)

f = The Darcy-Weisbach coefficient (0.02 for a smooth soil surface was used in this analysis)

ρ = Water density (pounds per cubic foot)

[337] Shear stress is the force per unit area acting parallel to the surface of an object, measured in pounds per square foot in this study.
[338] Chen and Anderson, 1986
[339] The critical shear stress of short grass is 0.6 pounds per square foot (28.7 pascals) according to Chen and Anderson, 1986.
[340] Chen and Anderson, 1986

V = Local velocity[341] (feet per second)

Once the initial breaching has begun, the erosion rate was estimated using two methods that were developed to determine the erosion of highway embankments based on field and laboratory test data. The first method is based solely on erodibility of the embankment soil and is calculated from shear stresses. This method does not account for vegetative cover. The erosion rate for non-cohesive soils using this method is given by the following formula:[342]

$$E = 0.00324(\tau - \tau_c)^{1.3}$$

Where,

E = Erosion rate (cubic feet per square foot per second)

τ = Shear stress (pounds per square foot, from previous formula)

τ_c = Critical shear stress of soil (0.1 pounds per square foot [2.4 pascals] applicable to silt loam was used in this analysis)

The second method is an empirical method considering soil type, vegetative cover, embankment height, overtopping depth, and head differential.[343] The erosion rates under both methods are calculated in terms of cubic feet of soil per second per square foot of embankment area, and then converted to inches per second of erosion in the direction progressing into the embankment.

For the I-10 roadway segment, it is expected that erosion may occur on either the inland side of the embankment due to storm surge flows or on the seaside of the embankment due to ebb flows as the surge retreats back to the ocean. Therefore, flow rates were evaluated over the entire storm surge hydrograph and the maximum discharges were selected for breach analysis. It is also possible that local velocities on the embankment slope may vary; however, for simplification, the velocities calculated from the peak discharges based on the above weir equations were used. The relevant parameters and outputs of the embankment breaching analysis are provided in Table 41.

Both overtopping storm surge scenarios have the potential to create sufficient flow velocities and shear stresses to cause erosion of the embankment. Based on the embankment breaching analysis, the maximum local shear stress produced by the Hurricane Katrina Shifted Scenario and the Hurricane Katrina Shifted + Intensified + SLR Scenario storm surge flows are 1.7 and 2.7 pounds per square foot (81.4 and 129.3 pascals), respectively, which both exceed the permissible shear stress of 0.1 pounds per square foot (2.4 pascals) applicable to silt loam.

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[341] The local velocity is defined as the flow velocity near the surface of the embankment, which may differ from the average velocity based on the discharges calculated from the weir equations. Chen and Anderson, 1986 provide velocity profiles of flow down an embankment. For simplicity, this study uses the velocity derived from the discharges calculated from the weir equations.
[342] Chen and Anderson, 1986
[343] See Chen and Anderson, 1986 for more details on this method. This method involves the use of a series of nomographs (graphical calculating devices) based on mathematical models to determine the erosion rate of an embankment.

Table 41: Summary of the I-10 Roadway Embankment Breaching Parameters

	Hurricane Katrina Base Case Scenario[344]	Hurricane Katrina Shifted Scenario	Hurricane Katrina Shifted + Intensified + SLR Scenario
Max. Discharge Over Roadway in cfs (m^3/s)	--	13,693 (388)	48,431 (1,371)
Velocity Based on Max. Discharge in ft/s (m/s)	--	3.3 (1.0)	4.2 (1.3)
Max. Local Shear Stress in lb/sq ft (Pa)	--	1.7 (81.4)	2.7 (129.3)
Estimated Max. Rate of Embankment Erosion Based on Soil Erodibility in Inch/s (cm/s)	--	0.1 (0.2)	0.1 (0.3)
Estimated Max. Rate of Embankment Erosion Based on Empirical Method in Inch/s (cm/s)	--	0.1 (0.13)	0.2 (0.5)

Also, as shown in the table, the two methods of estimating rate of embankment erosion produced comparable erosion rates. Taking the more extreme case of the two estimation methods, the Hurricane Katrina Shifted Scenario erodes the embankment at a rate of 0.1 inches per second (0.2 centimeters per second) and the Hurricane Katrina Shifted + Intensified + SLR Scenario erodes the embankment at a rate of 0.2 inches per second (0.5 centimeters per second).

It is important to note that the erosion rate values presented above are based on maximum discharges and headwater elevations over the embankment and are therefore maximum erosion rates, which are not likely sustained over the entire flood duration. To calculate the total erosion of the embankment during the entire storm surge, it is possible to sum the amount of erosion at various time steps over the flood duration based on the erosion rates calculated from the velocities and shear stresses at each time step. However, for simplification in this analysis, the maximum erosion rates listed above were multiplied by the amount of time during which 80% to 100% of the maximum velocity was sustained over the storm surge hydrograph according to the time-step analysis. These duration times were the same for both surge flows and ebb flows: 2.5 hours for the Hurricane Katrina Shifted Scenario and two hours for the Hurricane Katrina Shifted + Intensified + SLR Scenario. This approximation may underestimate the actual total erosion that could occur, but it provides an idea of the scale of possible erosion. If adaptation actions were to actually be contemplated at this facility, a calculation of erosion rates by time step should be conducted.

[344] The analysis was not performed for this scenario since the Hurricane Katrina Base Case Scenario surge is not expected to overtop I-10.

At these erosion rates and estimated duration times, it was estimated that the Hurricane Katrina Shifted Scenario storm surge would erode 60 feet (18.3 meters) into both the inland and seaside embankments, causing failure of the shoulder lane and four travel lanes on both sides of the roadway. The Hurricane Katrina Shifted + Intensified + SLR Scenario storm surge would erode 114 feet (34.7 meters) into both the inland and seaside embankments, which would result in breaching of the entire width of the roadway. Note that this analysis does not account for pavement interaction with flows (it is assumed that erosion of the embankment slopes will immediately undermine the pavement).

Flood Volume Entering Oakdale Neighborhood and Time to Drain

The degree of potential inland flooding was analyzed for the Oakdale neighborhood in order to determine flooding elevations and the time period during which the neighborhood would be flooded. These are important factors in predicting flood damage and emergency response planning. In order to determine the total volume of storm surge flows entering the Oakdale neighborhood, a time-step analysis was performed using the storm surge hydrographs (see Figure 82). The primary flow paths into the neighborhood included overtopping of the I-10 roadway and discharge through the three underpasses for Broad Street, the Tennessee Street and Railroad Underpass, and Warren Street. Discharges over the I-10 roadway were calculated based on the weir equations (see previous sub-section) and discharges through the underpasses were calculated using the Federal Highway Administration (FHWA) tidal hydraulics orifice approach.[345] The base equation is similar to the orifice equation; however, the discharge coefficient includes entrance, exit, and friction losses. The formulas for flow rate through the underpasses and for the discharge coefficient are as follows:

$$Q = C_d A\sqrt{2g\Delta H}$$

$$C_d = \left[1 \div \left(K_o + K_b + \frac{2gn^2 L_c}{K^2 h_c^{4/3}}\right)\right]^{1/2}$$

Where,

Q = Flow rate (cubic feet per second)

C_d = Discharge coefficient

A = Flow area

ΔH = Head differential[346]

K_o = Velocity head loss coefficient on the ocean side[347]

[345] The tidal hydraulics orifice approach was developed by FHWA for the hydraulic evaluation of bridges in tidal waterways (see FHWA, 2004). This flow rate approximation is typically applicable to waterways such as inlets connecting the ocean to a bay.
[346] In this formula, the head differential is taken as the difference between the storm surge flood elevation and the inland flood elevation above the bottom of the underpass. The head differential varies over the duration of the storm surge.

K_b = Velocity head loss coefficient on the inland side[348]

g = Gravitational constant (32.2 feet per second squared [9.8 meters per second squared)

n = Manning's roughness coefficient of the underpass (0.02 used for concrete)

L_c = Length of underpass

h_c = Depth of flow in underpass

To incorporate the discharge formulas into the time-step analysis, stage-discharge curves were developed to capture varying flow area geometries and head differentials across the underpasses at varying flood elevations. A stage-volume curve was also developed for the Oakdale neighborhood to determine the inland flood elevation at various volumes of flows entering the neighborhood, which was also incorporated into the time-step analysis. Table 42, Table 43, and Table 44 provide a summary of the time-step analysis of storm surge flows. The tables summarize seaward and inland flood elevations, flow rates and velocities over the I-10 roadway embankment and all three underpasses, and the erosion rate of the I-10 embankment based on the flow velocities. The erosion rates documented in these tables are calculated using only the first estimation method presented above, based on erodibility of embankment soil and the erosion rate equation. The positive flow rates and velocities indicate flows approaching inland, and the negative flow rates and velocities indicate flows returning seaward. Table 45 summarizes the total volume of storm surge flows entering the Oakdale neighborhood, the time to reach the peak flood elevation in the neighborhood, and the time for the flows to drain from the neighborhood under the three storm surge scenarios.

The results of the time-step storm surge flooding analysis allow for several conclusions to be made. First, the flow rates through the underpasses and over the I-10 roadway were significant enough for the inland flood elevations to grow at rates almost equal to that of the storm surge flood elevations. In other words, the rate of surge rise is slow enough where the underpasses can handle all the flow with little attenuation, and the limited inland capacity to hold the flood volume allows inland flood elevations to rise quickly. As a result, the time to reach peak flood elevation in the inland neighborhood was close to the time to the storm surge peak, as denoted by the crest in the storm surge hydrographs (see Figure 82). As such, the I-10 roadway embankment does not provide significant attenuation of storm surge flows as flooding enters the Oakdale neighborhood.

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347 Velocity head loss coefficient on the ocean side is taken as one if the velocity goes to zero.
348 Velocity head loss coefficient on the inland side is taken as one if the velocity goes to zero.

Table 42: Time-Step Analysis of Storm Surge Flows Along the I-10 Study Segment under the Hurricane Katrina Base Case Scenario

Time (hrs)	Flood Elevation Seaward (ft)	Flood Elevation Inland (ft)	Water Depth Above I-10 Roadway Low Point (ft)	Flow Rate Over I-10 Roadway (cuft/s)	Velocity Over I-10 Roadway (ft/s)	Flow Rate Through Broad St. (cuft/s)	Velocity Through Broad St. (ft/s)	Flow Rate Through TN St. (cuft/s)	Velocity Through TN St. (ft/s)	Flow Rate Through Warren St. (cuft/s)	Velocity Through Warren St. (ft/s)	Erosion Rate of I-10 Embankment (inch/s)
4.5	11.35	11.50	0	0	0	0	0	0	0	0	0	0
5.0	11.84	11.62	0	0	0	0	0	48	1.5	0	0	0
5.5	11.99	11.75	0	0	0	0	0	83	1.9	0	0	0
6.0	12.33	12.06	0	0	0	0	0	215	3.1	0	0	0
6.5	12.65	12.54	0	0	0	0	0	329	3.4	0	0	0
7.0	12.92	12.92	0	0	0	0	0	344	2.9	0	0	0
7.5	13.02	13.02	0	0	0	0	0	186	1.5	0	0	0
8.0	13.00	13.00	0	0	0	0	0	-69	-0.5	0	0	0
8.5	12.93	12.93	0	0	0	0	0	-168	-1.3	0	0	0
9.0	12.65	12.65	0	0	0	0	0	-292	-2.5	0	0	0
9.5	12.55	12.55	0	0	0	0	0	-137	-1.4	0	0	0
10.0	12.22	12.26	0	0	0	0	0	-219	-2.5	0	0	0
10.5	11.87	12.04	0	0	0	0	0	-155	-2.4	0	0	0
11.0	11.38	11.85	0	0	0	0	0	-130	-2.7	0	0	0
11.5	10.83	11.71	0	0	0	0	0	-86	-2.6	0	0	0
12.0	10.21	11.62	0	0	0	0	0	-45	-1.9	0	0	0
12.5	9.85	11.50	0	0	0	0	0	-11	-0.6	0	0	0

Table 43: Time-Step Analysis of Storm Surge Flows Along the I-10 Study Segment under the Hurricane Katrina Shifted Scenario

Time (hrs)	Flood Elevation Seaward @ I-10 Roadway (ft)	Flood Elevation Seaward @ Underpasses (ft)	Flood Elevation Inland (ft)	Water Depth Above I-10 Roadway Low Point (ft)	Flow Rate Over I-10 Roadway (cuft/s)	Velocity Over I-10 Roadway (ft/s)	Flow Rate Through Broad St. (cuft/s)	Velocity Through Broad St. (ft/s)	Flow Rate Through TN St. (cuft/s)	Velocity Through TN St. (ft/s)	Flow Rate Through Warren St. (cuft/s)	Velocity Through Warren St. (ft/s)	Erosion Rate of I-10 Embankment (inch/s)
3.0	11.32	11.32		0	0	0	0	0	0	0	0	0	0
3.5	12.30	12.30	11.50	0	0	0	0	0	238	3.5	0	0	0
4.0	13.25	13.25	11.92	0	0	0	0	0	828	5.7	0	0	0
4.5	15.38	14.33	13.05	0.78	163	2.6	526	5.3	1,460	5.9	497	5.4	0.040
5.0	16.10	15.48	13.97	1.50	948	2.9	1,208	6.3	2,421	6.6	1,300	6.4	0.053
5.5	16.81	16.59	15.48	2.21	2,751	3.3	1,595	5.6	2,805	5.8	1,764	5.7	0.076
6.0	17.70	17.70	16.59	3.10	5,085	2.9	2,210	5.7	3,614	5.8	2,461	5.8	0.054
6.5	18.64	18.64	17.70	4.04	8,627	2.9	2,522	5.3	3,960	5.4	2,808	5.3	0.053
7.0	19.43	19.43	18.64	4.83	11,945	2.8	2,714	4.9	4,151	4.9	3,017	4.9	0.050
7.5	20.02	20.02	19.43	5.42	13,693	2.6	2,612	4.2	3,928	4.3	2,897	4.3	0.040
8.0	20.29	20.29	20.02	5.69	11,195	2.0	1,834	2.8	2,739	2.9	2,032	2.9	0.018
8.5	20.24	20.24	20.29	5.64	-6,018	-1.1	-815	-1.3	-1,218	-1.3	-903	-1.3	0.003
9.0	19.90	19.90	20.24	5.30	-11,985	-2.1	-2,040	-3.2	-3,051	-3.2	-2,260	-3.2	0.023
9.5	19.22	19.22	19.90	4.62	-13,753	-2.8	-2,742	-4.5	-4,137	-4.6	-3,042	-4.6	0.046
10.0	18.42	18.42	19.22	3.82	-10,922	-2.8	-2,628	-4.9	-4,046	-5.0	-2,923	-5.0	0.049
10.5	17.65	17.65	18.42	3.05	-7,071	-2.7	-2,168	-4.8	-3,434	-4.8	-2,415	-4.8	0.042
11.0	16.80	16.80	17.65	2.20	-4,475	-2.7	-1,913	-5.0	-3,135	-5.1	-2,129	-5.1	0.042
11.5	15.91	15.91	16.80	1.31	-2,125	-2.6	-1,527	-5.0	-2,641	-5.2	-1,692	-5.1	0.040
12.0	15.17	15.17	15.91	0.57	-660	-2.8	-1,023	-4.5	-1,927	-4.7	-1,117	-4.6	0.049
12.5	14.44	14.44	15.17	0	-90	-2.5	-715	-4.3	-1,519	-4.6	-756	-4.4	0.035

Time (hrs)	Flood Elevation Seaward @ I-10 Roadway (ft)	Flood Elevation Seaward @ Underpasses (ft)	Flood Elevation Inland (ft)	Water Depth Above I-10 Roadway Low Point (ft)	Flow Rate Over I-10 Roadway (cuft/s)	Velocity Over I-10 Roadway (ft/s)	Flow Rate Through Broad St. (cuft/s)	Velocity Through Broad St. (ft/s)	Flow Rate Through TN St. (cuft/s)	Velocity Through TN St. (ft/s)	Flow Rate Through Warren St. (cuft/s)	Velocity Through Warren St. (ft/s)	Erosion Rate of I-10 Embankment (inch/s)
13.0	13.77	13.77	14.44	0	0	0	-417	-3.9	-1,103	-4.3	-404	-3.9	0
13.5	13.05	13.05	13.77	0	0	0	0	0	-835	-4.3	-142	-3.4	0
14.0	12.60	12.60	13.05	0	0	0	0	0	-418	-3.2	0	0	0
14.5	12.01	12.01	12.60	0	0	0	0	0	-312	-3.4	0	0	0
15.0	11.45	11.45	12.17	0	0	0	0	0	-180	-3.1	0	0	0
15.5	10.98	10.98	11.91	0	0	0	0	0	-105	-2.7	0	0	0
16.0	10.53	10.53	11.75	0	0	0	0	0	-55	-2.1	0	0	0
16.5	10.09	10.09	11.65	0	0	0	0	0	-21	-1.1	0	0	0
17.0	9.75	9.75	11.58	0	0	0	0	0	0	0	0	0	0

Table 44: Time-Step Analysis of Storm Surge Flows Along the I-10 Study Segment under the Hurricane Katrina Shifted + Intensified + SLR Scenario

Time (hrs)	Flood Elevation Seaward @ I-10 Roadway (ft)	Flood Elevation Seaward @ Underpasses (ft)	Flood Elevation Inland (ft)	Water Depth Above I-10 Roadway Low Point (ft)	Flow Rate Over I-10 Roadway (cuft/s)	Velocity Over I-10 Roadway (ft/s)	Flow Rate Through Broad St. (cuft/s)	Velocity Through Broad St. (ft/s)	Flow Rate Through TN St. (cuft/s)	Velocity Through TN St. (ft/s)	Flow Rate Through Warren St. (cuft/s)	Velocity Through Warren St. (ft/s)	Erosion Rate of I-10 Embankment (inch/s)
4.0	11.01	11.01	11.50	0	0	0	0	0	0	0	0	0	0
4.5	12.28	12.28	11.91	0	0	0	0	0	231	3.5	0	0	0
5.0	13.17	13.17	12.96	0	0	0	0	0	762	5.5	0	0	0
5.5	15.26	14.15	14.15	0.66	113	2.6	425	5.0	1,298	5.7	380	5.0	0.037
6.0	15.94	15.32	15.32	1.34	707	2.8	985	5.5	2,030	5.8	1,052	5.6	0.050
6.5	16.65	16.43	16.35	2.05	2,228	3.2	1,516	5.6	2,703	5.8	1,673	5.7	0.070
7.0	17.69	17.69	17.69	3.09	5,379	3.1	2,424	6.3	3,965	6.4	2,698	6.4	0.064
7.5	18.89	18.89	18.89	4.29	10,757	3.2	3,008	6.0	4,681	6.1	3,348	6.1	0.069
8.0	20.25	20.25	20.25	5.65	20,286	3.6	4,121	6.4	6,161	6.5	4,566	6.5	0.095
8.5	21.58	21.58	21.58	6.98	31,090	3.8	5,023	6.4	7,278	6.4	5,530	6.4	0.110
9.0	22.87	22.87	22.87	8.27	42,907	4.0	5,915	6.3	8,340	6.4	6,467	6.4	0.123
9.5	23.88	23.88	23.88	9.28	48,431	3.8	5,924	5.6	8,184	5.6	6,441	5.6	0.105
10.0	24.51	24.51	24.51	9.91	45,242	3.2	5,001	4.4	6,821	4.4	5,418	4.4	0.067
10.5	24.77	24.77	24.77	10.17	33,835	2.3	3,319	2.8	4,503	2.9	3,591	2.9	0.027
11.0	24.96	24.96	24.96	10.36	31,220	2.0	2,930	2.5	3,960	2.5	3,167	2.5	0.020
11.5	24.80	24.80	24.80	10.20	-29,301	-1.9	-2,697	-2.3	-3,645	-2.3	-2,915	-2.3	0.017
12.0	24.19	24.19	24.19	9.59	-47,020	-3.2	-5,096	-4.3	-6,910	-4.4	-5,512	-4.4	0.066
12.5	23.02	23.02	23.02	8.42	-54,136	-4.0	-6,601	-6.0	-9,062	-6.1	-7,164	-6.1	0.123
13.0	21.59	21.59	21.59	6.99	-46,049	-4.2	-6,341	-6.7	-8,914	-6.7	-6,927	-6.7	0.138
13.5	20.32	20.32	20.32	5.72	-30,636	-3.8	-4,911	-6.2	-7,114	-6.3	-5,406	-6.3	0.105

Time (hrs)	Flood Elevation Seaward @ I-10 Roadway (ft)	Flood Elevation Seaward @ Underpasses (ft)	Flood Elevation Inland (ft)	Water Depth Above I-10 Roadway Low Point (ft)	Flow Rate Over I-10 Roadway (cuft/s)	Velocity Over I-10 Roadway (ft/s)	Flow Rate Through Broad St. (cuft/s)	Velocity Through Broad St. (ft/s)	Flow Rate Through TN St. (cuft/s)	Velocity Through TN St. (ft/s)	Flow Rate Through Warren St. (cuft/s)	Velocity Through Warren St. (ft/s)	Erosion Rate of I-10 Embankment (inch/s)
14.0	19.18	19.18	19.18	4.58	-19,569	-3.4	-3,825	-5.9	-5,708	-6.0	-4,236	-5.9	0.081
14.5	18.23	18.23	18.23	3.63	-11,416	-3.0	-2,843	-5.3	-4,381	-5.4	-3,161	-5.4	0.058
15.0	17.41	17.41	17.41	2.81	-6,469	-2.7	-2,147	-4.9	-3,427	-5.0	-2,392	-5.0	0.043
15.5	16.59	16.59	16.59	1.99	-3,653	-2.6	-1,756	-4.9	-2,916	-5.0	-1,953	-4.9	0.039
16.0	15.77	15.77	15.77	1.17	-1,642	-2.5	-1,375	-4.8	-2,418	-5.0	-1,521	-4.9	0.036
16.5	15.23	15.23	15.23	0.63	-482	-2.8	-825	-3.8	-1,583	-4.0	-897	-3.9	0.046
17.0	14.53	14.53	14.53	0	-104	-2.5	-718	-4.2	-1,507	-4.5	-762	-4.3	0.037
17.5	13.88	13.88	13.88	0	0	0	-448	-3.9	-1,140	-4.3	-442	-4.0	0
18.0	13.35	13.35	13.35	0	0	0	0	0	-762	-3.8	-159	-3.1	0
18.5	12.74	12.74	12.74	0	0	0	0	0	-598	-3.9	-7	-2.1	0
19.0	12.24	12.24	12.28	0	0	0	0	0	-333	-3.2	0	0	0
19.5	11.77	11.77	12.02	0	0	0	0	0	-186	-2.8	0	0	0
20.0	11.26	11.26	11.83	0	0	0	0	0	-132	-2.9	0	0	0
20.5	10.88	10.88	11.70	0	0	0	0	0	-75	-2.3	0	0	0
21.0	10.52	10.52	11.62	0	0	0	0	0	-37	-1.6	0	0	0
21.5	10.16	10.16	11.50	0	0	0	0	0	-11	-0.6	0	0	0

Table 45: Flood Volumes Entering Oakdale Neighborhood and Time to Drain with Existing Structures

	Hurricane Katrina Base Case Scenario	Hurricane Katrina Shifted Scenario	Hurricane Katrina Shifted + Intensified + SLR Scenario
Total Volume in ac-ft (m^3)	40 (51,700)	1,300 (1,581,300)	2,800 (3,411,900)
Time to Peak Flood Elevation in Hours	3	5	7
Time to Drain after Peak in Hours	5	9	10.5

It can also be observed that the time to drain is longer than the time to peak, which may be partly due to the slower rate at which the storm surge subsides compared to the rate at which it rises. During the ebb of the surge when it retreats to the sea, the flood volume in the neighborhood drains at a slower rate than the flood levels south and east of the highway. It takes approximately 1.5 to two hours for the water elevations inland of the roadway (in the Oakdale neighborhood) to reach a comparable elevation to that on the seaward side. It is important to note, however, that the estimated time to drain may be less if a larger cross sectional flow area due to the eroded portion of the I-10 roadway embankment is taken into account.

<u>Flow Velocities through Underpasses</u>

Flow rates and velocities through the Broad Street, the Tennessee Street and Railroad, and the Warren Street bridge underpasses were examined to evaluate potential impacts to the bridge abutments and roadways under the bridge. The flow calculations were performed using the FHWA tidal hydraulics orifice approach which was incorporated into the time-step analysis of the storm surges (see previous section) to determine the maximum flow velocities through the underpasses. The results are summarized in Table 46.

Table 46: Peak Flow Velocities through the I-10 Study Segment Underpasses with Existing Structures

	Hurricane Katrina Base Case Scenario ft/s (m/s)	Hurricane Katrina Shifted Scenario ft/s (m/s)	Hurricane Katrina Shifted + Intensified + SLR Scenario ft/s (m/s)
Broad Street Underpass	--	6.3 (1.9)	6.7 (2.0)
Tennessee Street and Railroad Underpass	3.4 (1.0)	6.6 (2.0)	6.8 (2.1)
Warren Street Underpass	--	6.4 (1.9)	6.7 (2.0)

All three bridge crossings within the study site have concrete abutments and concrete roadways under the bridges. Since concrete has permissible velocities up to 18 feet per second (5.5 meters per second) or greater,[349] the majority of the roadway is protected from erosive flow velocities for all storm surge scenarios. However, small sections of median consist of soil and grass, with maximum permissible velocities of only two to four feet per second (0.6 to 1.2 meters per second); lower than or within the range of the projected velocities under each of the surge scenarios. This may be of concern because the bridge piers are located in the grass median. In addition, the Tennessee Street underpass also contains a railroad line. Railroad ballast, assuming two inch (5.1 centimeter) average stone size, has a maximum permissible velocity of three to six feet per second (0.9 to 1.8 meters per second).[350] Thus, the rail line might be vulnerable to the flow velocities under each surge scenario as well.

Step 6 – Identify Adaptation Option(s)

Multiple adaptive concepts were evaluated to address the issues identified with the existing facility in Step 5. The concepts consider what could be done to limit overtopping of I-10, embankment erosion, flooding impacts to the Oakdale neighborhood, and damage to the underpasses from high flow velocities.

The possibility of improvements to I-10 for the purpose of providing flooding protection to the Oakdale neighborhood was immediately ruled out because use of the roadway in this manner exceeds the overall design considerations and standards for the roadway. Additionally, the repurposing of any roadway as a flood protection structure will open the owner / agency up to additional liability concerns in the event that an extreme event breaches the roadway. Given that flood protection is not the primary function of a roadway and that a roadway will fall short of the design standards necessary for a flood protection structure, FHWA currently recommends against owner agencies pursuing this manner of adaptation. For these reasons, this adaptation option was not evaluated in this case study.

The adaptive concepts are first presented with their advantages and disadvantages. This is followed by a more in-depth discussion of the adaptation options that were developed considering differing combinations and variants of the adaptive concepts.

- **Widen Underpass(es) by Lengthening the Bridge(s)**

  Description:

  This concept involves lengthening one or more of the bridges to widen the underpass(es).

  Advantages:

  – Decreases flow velocities through the underpasses

  Disadvantages:

  – Relatively large capital and maintenance cost

[349] Fischenich, 2001
[350] Fischenich, 2001

– Major disruption to traffic for long periods of time during construction

Analysis showed that widening the underpasses decreases flow velocities through the underpasses, but not by a significant amount. This is due to the fact that the existing underpasses have capacity to convey the storm surge flows inland without significant attenuation, and the limited inland volume capacity causes the inland flood elevation to rise quickly, keeping the head differential[351] across the underpasses low. Thus, widening the underpasses does not cause a significant decrease in the head differential. Even with significant widening (for example by five times the original width), maximum velocities through the underpasses only decrease from 3.4 to 2.5 feet per second (one to 0.8 meters per second) for the Hurricane Katrina Base Case Scenario storm surge, from 6.6 to 5.8 feet per second (two to 1.8 meters per second) for the Hurricane Katrina Shifted Scenario, and 6.8 to 6.7 feet per second (2.1 to two meters per second) for the Hurricane Katrina Shifted + Intensified + SLR Scenario. Underpass widening may be a more reasonable option at project sites with more flow constriction through the underpasses or larger inland volume capacity. However, at this study site, this concept was excluded from the subsequent evaluation of adaptation options because it would be a large project undertaking with large capital cost and minimal effect on flow velocities.

- **Harden Underpass**

Description:

This concept involves hardening grassed areas within one or more of the underpasses with concrete and converting the segment of the railroad track at the Tennessee Street and Railroad underpass to a direct-fixation track.[352]

Advantages:

– Protects the bridge structures by preventing erosion of the areas within the underpasses
– Relatively low capital and maintenance cost

Disadvantages:

– Disruption to traffic during construction
– Requires installation of concrete approach slabs beneath the ballasted track to transition between the ballasted and the direct-fixation segments of the track

- **Raise I-10 Roadway**

Description:

This involves raising the I-10 roadway at the low point to protect the embankment from overtopping flows.

Advantages:

– Protects I-10 roadway from flood overtopping depending on proposed roadway elevation

[351] Head differential in this case is the difference between the storm surge flood elevation and the inland flood elevation above the top of the roadway.
[352] A direct fixation track involves rail attached to concrete plinths (platforms) mounted on concrete slabs

Disadvantages:

- Relatively large capital cost
- Major disruption to traffic for long periods of time during construction
- May require retaining wall if lateral right-of-way is insufficient for proposed roadway elevation

- **Armor I-10 Roadway Embankment**

Description:

This involves armoring the I-10 roadway embankment with vegetated, permanent reinforcement matting.

Advantages:

- Protects the I-10 roadway embankment slopes from erosion and prevents breaching
- Relatively low capital cost
- Low disruption to traffic

Disadvantages:

- Does not prevent flood overtopping
- Requires periodic maintenance and replanting when necessary

The option of raising the base of the underpass by approximately one foot (0.3 meters) to prevent the Hurricane Katrina Base Case Scenario storm surge from entering was also considered as an alternative. However, the stream channel crossing under the I-10 embankment in the vicinity of the underpass would allow flood flows to enter despite raising the bottom elevation of the underpass. Doing this may also impose upon the FEMA regulated floodplain along Tennessee Street. This option was therefore excluded.

The discussions of adaptation options below provide examples of how the above adaptation concepts can be used in combination to mitigate the impacts of predicted storm surge flooding.

<u>Option One – Harden Underpasses (Tennessee Street and Railroad Underpass Only)</u>

Analysis in Step 5 showed that flooding of the underpasses will likely produce sufficiently high flow velocities through the underpasses that may undermine the grass median and eventually the bridge piers. The Tennessee Street and Railroad underpass is particularly vulnerable due to its lower elevation compared to the other two underpasses as well as the railroad track that passes through the underpass. To address these issues, this adaptation option involves hardening the grassed areas within the Tennessee Street and Railroad underpass with concrete and converting the segment of the railroad track to a direct-fixation track.

This option protects this underpass from erosive flow velocities that would be created by the Hurricane Katrina Base Case Scenario storm surge, which reaches a flood elevation of 13 feet (four meters) and causes flooding of the Tennessee Street and Railroad underpass that leads to the flooding of a portion of the Oakdale neighborhood. Since no major changes to the dimensions and geometry of the underpasses or the I-10 roadway are proposed for this option, the flow rates, velocities, and degree of inland flooding remain unchanged compared to the

existing facility. Hardening the grassed areas with a non-erodible material such as concrete would help to prevent erosion of the soil and undermining of the bridge structure. Concrete, with a permissible flow velocity of over 18 feet per second (5.5 meters per second),[353] can resist the shear forces caused by flow velocities of up to 3.4 feet per second (one meter per second) experienced under the Hurricane Katrina Base Case Scenario at this underpass. The railroad ballast, assuming two inch (5.1 centimeter) diameter stone with a maximum permissible velocity of three to six feet per second (0.9 to 1.8 meters per second), may also be vulnerable to these flows. Converting the segment of railroad track at the underpass to a direct-fixation track will provide higher resistance to erosive forces compared to a ballasted track. This would also involve installation of concrete approach slabs beneath the ballasted track to transition between the ballasted and the direct-fixation segments of the track.

Option Two – Harden (All) Underpasses and Raise I-10 up to 21 feet (6.4 meters)

This option addresses the impacts associated with erosive flows through all three underpasses and overtopping of the I-10 roadway which can cause erosion of the embankment. This option involves the following measures:

- Elevating I-10 to 21 feet (6.4 meters) through raising the lowest point of the roadway by 6.4 feet (two meters).
- Hardening all grassed areas within all three underpasses with concrete and converting the segment of the railroad track at the Tennessee Street and Railroad underpass to a direct-fixation track

This option protects all three underpasses from erosive flow velocities that would be created by the Hurricane Katrina Shifted Scenario, which reaches a flood elevation of 20.3 feet (6.2 meters), causing flooding of all three underpasses and overtopping the existing I-10 roadway by 5.7 feet (1.7 meters). Analysis showed that raising the roadway to 21 feet (6.4 meters) only increases maximum flow velocities through the underpasses from approximately 6.6 feet (2.0 meters per second) to 6.9 feet per second (2.1 meters per second) during the Hurricane Katrina Shifted Scenario. Hardening the grassed areas within all three underpasses with a non-erodible material such as concrete, and converting the segment of railroad track at the Tennessee Street and Railroad underpass to a direct-fixation track in the same manner described under Option One, can resist shear forces caused by flow velocities at the underpasses of the Option Two facility.

This option would also prevent any overtopping of the I-10 roadway by the Hurricane Katrina Shifted Scenario storm surge flood and eliminate the potential for embankment erosion under this scenario. Analysis also showed that raising the roadway does not help to prevent storm surge flows from entering the neighborhood because the existing underpasses have significant capacity to convey storm surge flows inland, and the limited inland volume capacity causes the inland flood elevation to rise quickly. The underpasses have the capacity to convey all the flow with

[353] Fischenich, 2001

little attenuation, and thus the amount of inland flooding caused by the storm surge is virtually unaffected by the height of the roadway embankment. Therefore, this adaptation options does not significantly alter the amount of flooding in the neighborhood. This may not be the case at project sites with more flow constriction through the underpasses or larger inland volume capacity.

Option Three – Harden (All) Underpasses and Raise I-10 up to 26 feet (7.9 meters)

This option addresses the impacts associated with erosive flows through all three underpasses and overtopping of the I-10 roadway which can cause erosion of the embankment. This option involves the following measures:

- Elevating I-10 to 26 feet (7.9 meters) through raising the lowest point of the roadway by 11.4 feet (3.5 meters)
- Hardening all grassed areas within the underpasses with concrete and converting the segment of the railroad track at the Tennessee Street and Railroad underpass to a direct-fixation track

This option protects all three underpasses from erosive flow velocities that would be created by the Hurricane Katrina Shifted + Intensified + SLR Scenario, which reaches a flood elevation of 25 feet (7.6 meters), causing flooding of all three underpasses, and overtopping the existing I-10 roadway by 10.4 feet (3.2 meters). Analysis showed that raising the roadway to 26 feet (7.9 meters) only increases maximum flow velocities through the underpasses from approximately 6.8 feet (2.1 meters per second) to 7.2 feet per second (2.2 meters per second) during the Hurricane Katrina Shifted + Intensified + SLR Scenario. Hardening the grassed areas within all three underpasses with a non-erodible material such as concrete, and converting the segment of railroad track at the Tennessee Street & Railroad underpass to a direct-fixation track in the same manner described under Options One and Two, can resist shear forces caused by flow velocities at the underpasses of the Option Three facility.

This option would also prevent any overtopping of the I-10 roadway by the Hurricane Katrina Shifted + Intensified + SLR Scenario storm surge flood and eliminate the potential for embankment erosion under this scenario. As true in the case of Option Two, analysis also showed that raising the roadway does not help to prevent storm surge flows from entering the neighborhood because the rate of surge rise is slow enough where the underpasses can handle all the flow with little attenuation, and the amount of inland flooding caused by the storm surge is virtually unaffected by the height of the roadway embankment. Therefore, this adaptation option does not significantly alter the amount of flooding in the neighborhood. This may not be the case at project sites with more flow constriction through the underpasses or larger inland volume capacity.

Option Four – Harden (All) Underpasses and Armor I-10 Roadway Embankment

This option addresses the impacts associated with erosive flows through all three underpasses and over the I-10 roadway embankment. This option involves the following measures:

- Armoring both sides of the I-10 roadway embankment with vegetated, permanent reinforcement matting, within the segment that is subject to flooding
- Hardening all grassed areas within the underpasses with concrete and converting the segment of the railroad track at the Tennessee Street and Railroad Underpass to a direct-fixation track

This option protects all three underpasses and the I-10 roadway embankment from erosive flow velocities that would be created by the Hurricane Katrina Shifted + Intensified + SLR Scenario, which reaches a flood elevation of 25 feet (7.6 meters), causing flooding of all three underpasses and overtopping the existing I-10 roadway by 10.4 feet (3.2 meters). Instead of raising the roadway embankment, this option allows the roadway to be overtopped by storm surge flows while protecting the embankment slopes from the erosive flows with less erodible material.

Since no major changes to the dimensions and geometry of the underpasses or the I-10 roadway are proposed for this option, the flow rates, velocities, and time to drain inland flood waters remain unchanged compared to the existing facility. The material proposed for lining the embankment slopes is vegetated reinforcement matting composed of woven synthetic fibers or other permanent material. This material has a maximum permissible velocity of five to seven feet per second (1.5 to 2.1 meters per second) and shear stress of three to five pounds per square foot[354] (144 to 239 pascals) depending on the type. These materials are designed to a sufficient strength to withstand the maximum flow velocity of 4.2 feet per second (1.3 meters per second) and shear stress of 1.7 pounds per square foot (81.4 pascals) expected to be produced by the Hurricane Katrina Shifted + Intensified + SLR Scenario storm surge on the embankment. Using vegetation to resist erosive flows on the slopes will require periodic maintenance and possible replanting to preserve the integrity of the vegetation; however, frequent mowing is not necessary if seed mixes with certain herbaceous species are used, such as annual ryegrass, bermudagrass, tall fescue, weeping lovegrass, or annual lespedeza.[355] The areas requiring lining are both slopes of the embankment within the anticipated submerged segment of roadway, approximately 2,240 feet (683 meters) in length and three to 13.5 feet (0.9 to 4.1 meters) in height.

Hardening the grassed areas within all three underpasses with a non-erodible material such as concrete, and converting the segment of railroad track at the Tennessee Street and Railroad underpass to a direct-fixation track in the same manner described under Options One through Three, can resist shear forces caused by flow velocities at the underpasses.

Step 7 – Assess Performance of the Adaptation Option(s)

Table 47 summarizes how well each of the three proposed adaptation options performs under each of the storm surge scenarios. If these adaptation options actually were being considered for design, a full analysis quantifying the performance of each option under each scenario would need to be conducted and the results used in the economic analysis in Step 8.

[354] Fischenich, 2001
[355] ALDOT, 2012

Table 47: Performance Summary of the Adaptation Options for the I-10 Study Segment

	Hurricane Katrina Base Case Scenario	Hurricane Katrina Shifted Scenario	Hurricane Katrina Shifted + Intensified + SLR Scenario
Option One: Harden Underpass (Tennessee Street & Railroad Underpass Only)	• Protects the Tennessee Street & Railroad Underpass against erosive flow velocities	• Does not protect I-10 roadway embankment, Broad Street Underpass, or Warren Street Underpass against erosive flow velocities.	• Does not protect I-10 roadway embankment, Broad Street Underpass, or Warren Street Underpass against erosive flow velocities.
Option Two: Harden (All) Underpasses and Raise I-10 Roadway up to 21 feet (6.4 meters)	• Protects Tennessee Street & Railroad Underpass against erosive flow velocities.	• Prevents storm surge from overtopping I-10 roadway • Protects all three underpasses against erosive flow velocities.	• Protects all three underpasses against erosive flow velocities. • Does not protect I-10 roadway embankment from erosive flow velocities
Option Three: Harden (All) Underpasses and Raise I-10 Roadway up to 26 feet (7.9 meters)	• Protects Tennessee Street & Railroad Underpass against erosive flow velocities.	• Prevents storm surge from overtopping I-10 roadway • Protects all three underpasses against erosive flow velocities.	• Prevents storm surge from overtopping I-10 roadway • Protects all three underpasses against erosive flow velocities.
Option Four: Harden (All) Underpasses and Armor I-10 Roadway Embankment	• Protects Tennessee Street & Railroad Underpass against erosive flow velocities.	• Protects I-10 roadway embankment and all three underpasses from erosive flow velocities • Does not prevent storm surge from overtopping I-10 roadway	• Protects I-10 roadway embankment and all three underpasses from erosive flow velocities • Does not prevent storm surge from overtopping I-10 roadway

Step 8 – Conduct an Economic Analysis

An economic analysis was not conducted for this case study. Refer to Section 4.4.1 for an example of how an economic analysis can be conducted for an adaptation study. That said, a general comparisons of the benefits and relative costs of each adaptation option can provide a great deal of insight toward decision-making, even before a formal economic analysis is conducted. Priority should be given to protecting the assets with the highest value, which, for this study, are the bridges at the three underpasses and the railroad track. As shown in Table 47, hardening one or more the underpasses by replacing the grassed areas with concrete and replacing the railroad ballast with a direct fixation track will provide protection of the

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underpasses under all three storm surge scenarios. At a relatively low cost compared to the other options, this course of action is promising.

As for protection of the I-10 roadway, while raising the roadway would prevent storm surge flows from overtopping the roadway embankment, analysis has shown that this would have very little effect on the amount of inland flooding. The main concern would be potential erosion and breaching of the embankment, which can be mitigated by armoring the embankment slopes with vegetated reinforcement matting. A raised roadway may allow I-10 to remain functional during a storm surge event, but the relative benefit of being able to keep I-10 functioning as opposed to allowing it to flood would need to be conducted. Analysis may reveal that raising the roadway would provide minimal added benefit at much greater capital costs and disruption to traffic during construction compared to armoring the embankment.

Step 9 – Evaluate Additional Decision-Making Considerations

Additional considerations that address environmental and social concerns may influence the decision-making process. The following are potential action items specific to this study site that may need to be addressed when selecting adaptation alternatives:

- Community outreach and public involvement are necessary courses of action, particularly if the underpass widening option is considered. Widening bridges may cause concern among public stakeholders about potential increased flooding, construction disturbances, and costs. As such, public meetings would need to be held to explain the impacts and convey the facts to the public. Coordination with individual property owners would also be necessary if the adaptation is expected to impact specific properties.
- It may be necessary to develop (or revise existing) evacuation plans to reflect the storm surge flooding events predicted by this study. Evacuation schedule and emergency response coordination can be planned based on predicted storm surge peaking times and time for inland areas to drain. These activities should be closely coordinated with the local emergency management agency.
- Continued maintenance and asset management are necessary to ensure the integrity of the new facility. For example, if vegetative plantings and reinforcement matting are used on the embankment slopes, regular inspection and maintenance would be required to identify areas for replanting and ensure that the embankment is sufficiently protected against erosive flows.

Step 10 – Select a Course of Action

Although a formal economic analysis was not performed for the adaptation alternatives proposed, Option 4 provides the most protection against the impacts of storm surge flows for relatively low capital costs. Hardening the underpasses by replacing the grassed areas with concrete and replacing the railroad ballast with a direct fixation track provides protection of the underpasses under all three storm surge scenarios. Although some maintenance is necessary, armoring the embankment slopes with vegetated reinforcement matting can provide significant protection of the I-10 roadway embankment under all three storm surge scenarios.

Step 11 – Plan and Conduct Ongoing Activities

Whatever option is chosen, performance of the new facility should be monitored after completion of the project, and impacts to the facility should be periodically assessed. These activities will help to determine if design thresholds are being met and if so, whether the facility is meeting design goals. Potential additional improvements can then be evaluated based on monitoring and assessment findings, and any lessons learned can be applied to future projects. Agencies should also continue to monitor climate projections as they change with the advancement of climate knowledge and modeling capabilities.

Also, if one of the adaptation options involving vegetative plantings and reinforcement matting are used on the embankment slopes, regular inspection, maintenance, mowing and replanting would be required to ensure that the embankment is sufficiently protected against erosive flows.

Conclusions

This case study provides an example of how a road or rail alignment can be evaluated for climate change impacts resulting from storm surge flooding and sea level rise. The I-10 alignment between mileposts 24 and 25 was studied under three plausible future storm surge scenarios. It was determined that all storm surge scenarios could impact the Oakdale neighborhood north and west of the highway and cause potential erosion problems at the Tennessee Street and Railroad Underpass. The Hurricane Katrina Shifted Scenario and the Hurricane Katrina Shifted + Intensified + SLR Scenario would, in addition, present erosion problems at the other two underpasses, overtop I-10 and cause erosion concerns along the embankment at the location of overtopping. A variety of adaptation options were proposed to lessen the impacts of each storm surge scenario.

During the analysis it was found that the area that was most lacking in current research was the topic of embankment breaching. Many studies have aimed to establish estimates of flow rates and breach dimensions for earthen dams and levees, but not many have developed methods to predict the onset of embankment breaching, or that focus on highway embankments. This is an area of future research that would be needed in order to more accurately predict the impact of storm surge flooding on highway embankments.

4.4.7 Coastal Tunnel Exposure to Storm Surge – The I-10 (Wallace) Tunnel

Introduction

Underwater coastal tunnels are particularly vulnerable to storm surge. This section contains a brief summary of the study *Storm Surge Analysis for the I-10 Tunnel* performed by Douglass et al. (2007) on the I-10 tunnel under the Mobile Ship Channel, in which a "design storm" method for risk-based coastal design decisions was developed that closely matches the *General Process for Transportation Facility Adaptation Assessments*. This method was applied and the tunnel was found to have vulnerability to flooding in a hurricane. Various approaches to dealing with this issue have been developed, including replacing the tunnel with a bridge, and these are being assessed by ALDOT.

Case Study Highlights

Purpose: Evaluate whether an underwater coastal tunnel could be flooded during hurricane events due to surge entering air vents or the non-gated tunnel entrance.

Approach: This case study was adapted from a previous study conducted by Douglass et al (2007). Using a three-step modeling process to quantify the risk of flooding under present day conditions. The USACE ADCIRC model was used to simulate storm surge. The USACE EST model was used to estimate the storm surge frequency relationship. Then, a weir flow model and EurOtop (wave overtopping model) were used to model a flood hydrograph. These modeling efforts allowed Douglass et al. to estimate surge elevations for the 100-year and 150-year storm, and then compare the surge elevations to the engineering design of the tunnel.

Findings: Douglass et al (2007) found that the tunnel could be flooded during storms equal to or greater than the 75-year storm.

Viable Adaptation Options:

- Raise the west portal wall elevation
- Raise all approach walls
- Install temporary flood gates

Other Conclusions: The Saffir-Simpson Hurricane Category scale is not particularly useful for engineering decisions because hurricanes are assigned categories based on wind speeds, not storm surge.

Note that the Douglass study did not include an assessment of future sea level rise and accompanying higher storm surge. However, the analysis is included as a case study in this report to illustrate how the *General Process for Transportation Facility Adaptation Assessments* can be applied not only to climate change analyses but also to situations where estimates of current storm surge return periods are known to be out of date and new (higher) estimates of current surge probabilities are developed to reassess present day risk.[356]

Application of the General Process for Transportation Facility Adaptation Assessments

Step 1 – Describe the Site Context

The I-10 Tunnel (also known as the George C. Wallace Tunnel) crosses under the Mobile Ship Channel (the Mobile River) north of Mobile Bay (see Figure 83 and Figure 84). The tunnel is part of the interstate highway system and is located at the west end of a seven-mile elevated

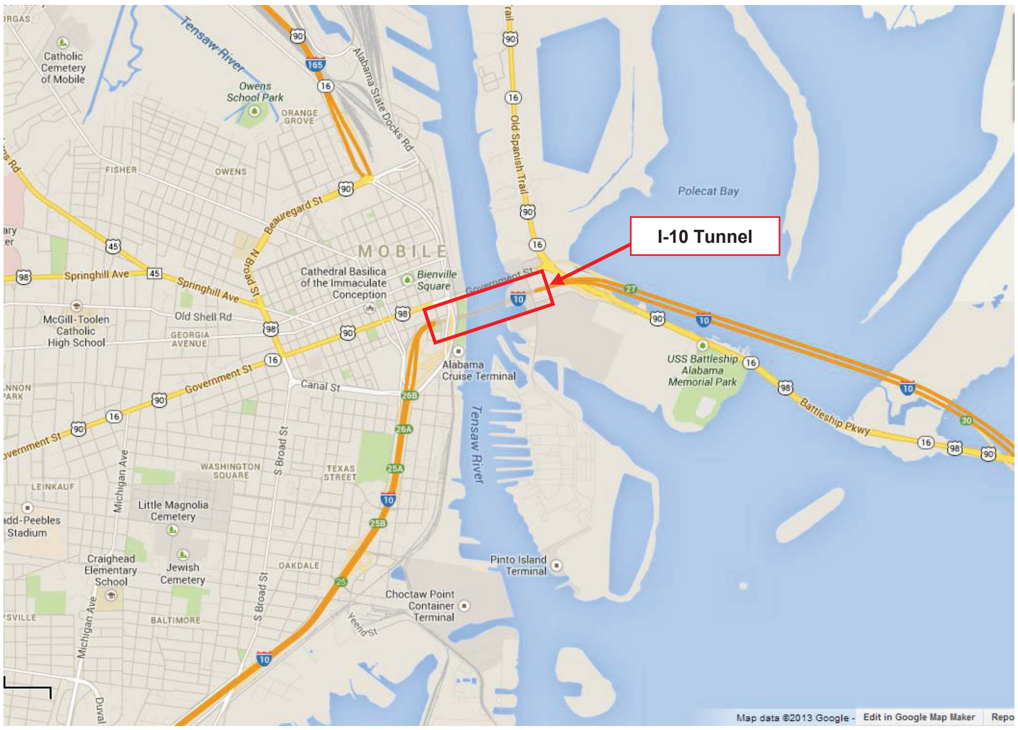
[356] Changes in flood elevations are a common situation when FEMA updates their flood mapping (both in coastal and riverine environments) or when NOAA updates their precipitation return period estimates as with the release of NOAA Atlas 14. As illustrated by this case study, the *General Process for Transportation Facility Adaptation Assessments* can be applied to reassess risks to facilities when these changes in present day flood elevation estimates are released.

causeway across the north end of Mobile Bay. The I-10 Tunnel carries Annual Average Daily Traffic (AADT) of about 70,000 vehicles per day and was designated as a critical asset by the analysis presented in the *Assessing Infrastructure for Criticality in Mobile, Alabama* report.[357]

Step 2 – Describe the Existing Facility

The I-10 Tunnel (opened in 1972) is 3,000 feet (914.4 meters) long and consists of twin tubes carrying two lanes of traffic each in each direction. The approaches total 1,300 feet (396.2 meters) in length. The existing crest elevation of the west portal wall (see Figure 85) is 16 feet[358] (4.9 meters) and the crest elevation of the east portal wall is 19 feet (5.9 meters).

Figure 83: Map Showing the Location of the I-10 Tunnel within the Mobile Metropolitan Area[359]



[357] USDOT, 2011
[358] All elevations in this study are relative to the North American Vertical Datum of 1988 (NAVD88) unless otherwise noted.
[359] Source of basemap: Google Maps (as modified)

Figure 84: Aerial Photograph of the I-10 Tunnel Location[360]

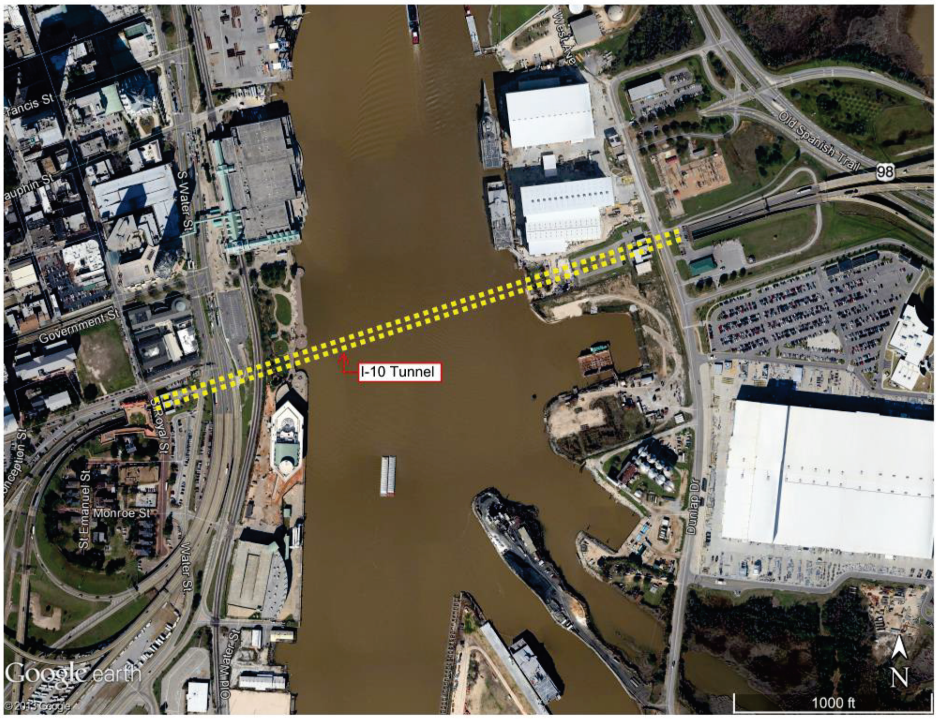


Figure 85: West Portal of the I-10 Tunnel[361]

[360] Source of basemap: Google Earth (as modified)
[361] Douglass, Scheffner, and Kellogg Brown & Root Services, Inc., 2007

Step 3 – Identify Environmental Stressors That May Impact Infrastructure Components

Storm surges, the primary environmental stressor that could affect the I-10 Tunnel, are the focus of this case study.

Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes

The I-10 Tunnel reports, *Storm Surge Analysis for the I-10 Tunnel*[362] and *Wave Overtopping Study Report for the I-10 Tunnel,*[363] analyzed storm surge and wave overtopping as the principal threat to the tunnel. The studies evaluated the vulnerability of the transportation asset to extreme events, however, they did not specifically consider climate change scenarios. That said, the methods and results have some aspects similar to climate change impacts. A component of the studies was the re-evaluation of the relationship between risk and storm surge and the result is a peak 100-year storm surge elevation three to four feet (0.9 to 1.2 meters) higher than the existing FEMA maps. This is similar in magnitude to a reasonable sea level rise scenario assumption for this area. At the time of this study, the existing FEMA flood maps were over 25 years old, the adjacent county to the west had just been restudied by FEMA, resulting in significant increases in the estimated flood levels, and FEMA efforts to restudy the basic surge-frequency relationship in Mobile County were years away from being completed. Hurricane Katrina had just caused the highest storm surge in the previous 50 years and it made landfall 100 miles from Mobile County. Thus, there was concern that the storm surge at the tunnel would have been much more severe had the storm made landfall closer to Alabama.

<u>Water Level Values</u>

Table 48 shows several of the more recent, measured, high water levels around the tunnel.

[362] Douglass et al., 2007
[363] Douglass, 2008

FHWA002877

Table 48: Historic High Water Marks near the I-10 Tunnel[364]

Rank	High Water Mark Elev. (ft. NAVD)	Storm Name	Date
1	12.4[365]	Katrina	2005
2	11.7	Frederic	1979
3	9.4	Georges	1998
4	7.4	Camille	1969
5	4.9	Ivan	2004
6	3.8	Elena	1985

Realizing the tunnel's vulnerability after Hurricane Katrina, Douglass et al. (2007) were tasked with developing a risk-based approach to coastal design decisions: specifically, the likelihood of the tunnel flooding during hurricanes. It is well understood that storm surge at a specific site is more sensitive to the track of the storm than the storm's "category" as measured on the Saffir-Simpson scale. The Saffir-Simpson scale is based on wind speed rather than storm surge, making it problematic for engineering decisions when storm surge is the damage mechanism. Traditional risk-based design return periods can be used effectively, however. The study team used a three-step modeling procedure to develop quantitative estimates of the risk of flooding in the existing tunnel according to present day climate conditions. The first two related modeling steps quantify the coastal storm surge–frequency relationship at any coastal location where tropical storms are a dominant phenomenon. The procedure has been developed by USACE and FEMA for coastal flood analysis and mapping. Two USACE computer models – ADCIRC (ADvanced CIRCulation Model for Oceanic, Coastal and Estuarine Waters) and the Empirical Simulation Technique (EST) model were used in these studies.

The ADCIRC model can be used to simulate tidal circulation and / or coastal storm surge. Other hydrodynamic models exist but ADCIRC is in the public domain and has proven capable of modeling coastal hydrodynamics at a high-resolution very well in a variety of situations. The study team included a coastal numerical modeling specialist (Dr. Norman Scheffner) as is typically required for the use of high-performance, high-resolution, hydrodynamic models like ADCIRC. Model validation for this study was done with both tidal simulations and storm surges. Storm events were verified by comparing simulated peak surge elevations to historical observations at the location of the tunnel. The model was then used to simulate all storms that

[364] Source: Douglass et al., 2007. Note: High-water marks are within the general vicinity of the I-10 Tunnel. These values are the higher elevation values reported along the north end of the bay. The values are relative to different datums and include NAVD88, mean sea level (the average of the water elevations recorded at each hour of the day over the current National Tidal Datum Epoch [the specific 19-year period over which NOAA uses to obtain observations that are used to develop tidal statistics]), and the National Geodetic Vertical Datum of 1929 (NGVD). The difference between these datums is less than 0.5 feet (15.2 centimeters).
[365] FEMA, 2006

significantly impacted the study area since 1886. In order to insure that the most possible severe events were included, simulations included hypothetical events that could occur. For example, the tracks of the most intense events were shifted along the coast such that the study area experienced maximum surge elevations.

In the second step in the modeling procedure, following all numerical simulations, the database of computed surges were used as input for the EST – a statistical model that simulates life-cycle sequences of cyclic but nondeterministic multi-parameter systems (such as storm events) and their corresponding environmental impacts. This approach can be used in place of a joint probability method for developing the storm surge–frequency relationship. A basic assumption of either method of assigning frequency to specific surge elevations is that future events will be statistically similar in magnitude and frequency to past events: again, climate change was not considered in this study.

The third step in the modeling procedure was flood hydrograph modeling using a combination of a weir[366] flow model and EurOtop, a wave overtopping model. The Douglass et al. (2007) study estimated the storm surge high water elevations are 16.7 feet (5.1 meters) for the 100-year (one percent annual exceedance probability) storm return period and 19 feet (5.8 meters) for the 150-year (0.7% annual exceedance probability) storm return period.[367]

Step 5 – Assess Performance of the Existing Facility

Past performance is a starting point to understanding the impacts under potential future storms. During Hurricane Katrina, the I-10 Tunnel experienced some limited flooding, including flooding of the air shafts due to failure of the outflow pipe, which led to back flow. Filling of air shafts can lead to closing of the tunnel because of the potential for carbon monoxide poisoning.

The following subsection discusses the critical flooding thresholds with respect to various potential storms as determined by Douglass et al. (2007).

<u>Flooding Threshold</u>

The results of the analyses show that the tunnel could flood during hurricanes as shown in Table 49. The 100-year storm surge elevation (i.e., the surge level with a 1% chance of exceedance in any year) is estimated at 16.7 feet (5.1 meters). The fourth and fifth columns of Table 49 give the risk of occurrence (of flooding) for two different design lives, 20 years and 50 years, for each of the return periods. These design lives, 20 years and 50 years, were selected for demonstration purposes only. The probability of that flood level being exceeded during a 20-year or 50-year

[366] A weir is a barrier across a river (smaller than a dam) characterized by the allowance of water to flow over the top of the barrier.
[367] Douglass et al., 2007

time period is 18% and 39%, respectively.[368] The risk values shown in these columns are derived using a form of the binomial distribution common in quantitative risk analysis.[369]

Table 49: Projected Storm Surge Flooding Elevations by Exceedance Probabilities for the I-10 Tunnel over Hypothetical Remaining Design Lifespans[370]

Storm Return Period (years)	Storm Surge Elevation (Ft. NAVD)	Probability of Exceedance in any Year	Probability of Exceedance in a 20-Year Design Life	Probability of Exceedance in a 50-Year Design Life	Estimated Flooding Levels in the I-10 Tunnel (Ft.)
25	9.8	4.0%	56%	87%	0
50	13.4	2.0%	33%	64%	0
75	15.4	1.3%	24%	49%	0-3
100	16.7	1.0%	18%	39%	Full
150	19.0	0.7%	13%	28%	Full
200	20.2	0.5%	10%	22%	Full

Step 6 – Identify Adaptation Option(s)

Previous work by others had recommended raising the elevation of the west portal wall to 19 feet (5.8 meters) to match the elevation of the east portal wall (**Option A**). The initial, primary goal of this study was to quantify the additional level of flood protection provided by such an approach. Interestingly, this study showed that such an approach alone would only provide a relatively limited level of additional flood protection because of wave overtopping at the more exposed east portal. Thus, the study evolved to consider several other adaptation options including:

- **Option B:** Raise all approach walls to elevation 19 feet (5.8 meters) and construct a berm / seawall around the east portal to reduce wave overtopping
- **Option C:** Install temporary flood gates. The surge-frequency analysis from this study indicates that extremely high surge levels could occur at this site. The only completely "storm-proof" alternative would be to close the tunnel with temporary flood gates to be deployed as large storms approached.[371]

Step 7 – Assess Performance of the Adaptation Option(s)

The study found the following results for the three adaptation options across the surge scenarios developed:

[368] Douglass, 2008
[369] See for example Equation 4.81 in FHWA, 2002a.
[370] Source: Douglass, 2008. Note: The estimated flooding levels are water depths in the low-point in the tunnel. These estimated depths include both wave overtopping and weir flow over the crest of the portal walls. "Full" means the entire tunnel will be filled with seawater.
[371] Douglass, 2010

- **Option A:** Raising all approach walls to elevation 19 feet (5.8 meters) would result in a relatively small additional level of flood protection: no flooding for the 75-year event, some very limited flooding for the 100-year event, and complete flooding for the 150-year event.[372]
- **Option B:** Raising all approach walls to elevation 19 feet (5.8 meters) and constructing a berm / seawall near the east portal could provide significantly more protection: no flooding for all scenarios up to the 150-year event.[373] A berm or seawall that extended to a high enough elevation would reduce or eliminate waves at the approach wall and thus reduce wave overtopping. This option is meant to reduce the waves incident on the approach walls, but will not prevent the surge from reaching the approach walls. Several things should be noted for this adaptation option. First, this option was developed to take advantage of some of the site-specific characteristics. Wave heights may be much higher immediately to the east of the east portal (see Figure 86) due to the lower ground elevation and because the service access road is not present to break up the waves (i.e., the waves are not depth-limited). Second, the potential for wave uplift forces on the first bridge span to the east of the east portal may be enough to cause failure of this seven-mile stretch of highway regardless of the protection provided by this adaptation option.[374]
- **Option C:** Temporary flood gates would protect the tunnel from all storms including catastrophic storms such as the 500-year event. ALDOT has experience with temporary flood gates used to protect the adjacent, older, smaller Bankhead Tunnel under the Mobile Shipping Channel. Significant operational issues related to closing an interstate highway during hurricane approach would have to be addressed.

The results for flooding under adaptation options A and B, as compared to existing conditions, are provided in Table 50.

[372] Douglass, 2008
[373] Douglass, 2010
[374] Douglass et al., 2007; Douglass, 2008; Douglass, 2010

Figure 86: Portion of I-10 Immediately East of the I-10 Tunnel Portal[375]

Table 50: Projected Water and Flooding Levels at the I-10 Tunnel with Adaptation Options A and B[376]

Storm Return Period (Years)	Storm Surge Elev. (ft. NAVD)	Existing I-10 Tunnel Lowest Wall Crest Elevation (Ft. NAVD)	Estimated Flooding Levels: Existing I-10 Tunnel (Ft. NAVD)	Estimated Flooding Levels: Option A – All Walls Raised to Elev. 19 (Ft. NAVD)	Estimated Flooding Levels: Option B – All Walls Raised to Elev. 19 + Berm / Seawall (Ft. NAVD)
25	9.8	16	0	0	0
50	13.4	16	0	0	0
75	15.4	16	0-3 ft.	0	0
100	16.7	16	Full	0-6 ft.	0
150	19.0	16	Full	Full	0-6 ft.
200	20.2	16	Full	Full	Full

Step 8 – Conduct an Economic Analysis

An economic analysis was not included in this portion of this case study but is recommended for facility-level adaptation assessments. Following this study, the tunnel's owner, ALDOT,

375 Douglass et al., 2007
376 Source: Douglass, 2008. Note: The estimated flooding levels are water depths in the low-point in the tunnel. These estimated depths include both wave overtopping and weir flow over the crest of the portal walls. "Full" means the entire tunnel will be filled with seawater.

developed construction cost estimates for each of the adaptation design options mentioned above.

Step 9 – Evaluate Additional Decision-Making Considerations

A number of additional decision-making considerations unique to this facility were required. First, the west portal of this tunnel is located in downtown Mobile immediately adjacent to several historically significant buildings including Fort Conde. This leads to several technically challenging issues related to the geotechnical and structural engineering which would be required for any adaptation option. Second, traffic congestion is an issue at the tunnel: in fact, there is an effort underway to replace the I-10 Tunnel under the Mobile Ship Channel with a large bridge to address the traffic delays typical at the tunnel. Third, as mentioned above, there are significant operational issues related to decisions to close an interstate highway tunnel with temporary flood gates if this adaptation option were to be chosen. The closure takes some time after the decision and thus would have to be done prior to the peak of the storm.

Step 10 – Select a Course of Action

A final design has not been selected for this case study. Selection of a final design will require further economic analysis and additional decision-making considerations be taken into account. ALDOT is still working on determining a course of action for the tunnel.

Step 11 – Plan and Conduct Ongoing Activities

Once a course of action has been decided on, ongoing monitoring activities should be conducted to assess whether the facility is performing as planned. Monitoring activities could include:

- Installing a recording tidal gage
- Establishing a log, that would record the details and dates of any climate stressor-related incident, and the performance of adaptation option pursued
- Noting updates of sea level projections such as those provided by the U.S. Army Corps of Engineers

If an adaptation option is pursued, estimates of the cost savings due to the adaptations should be calculated to track the value they are providing.

Conclusions

Several lessons can be learned from this coastal tunnel case study. First, adaptation decisions should be based upon sound science and site-specific engineering analysis. This includes selection of appropriate storm surge and wave computer models by experienced coastal engineers on the study team who know how to quantify risk (from storm surge), know the physical processes and damage mechanisms to look at, and which models will give most accurate results. Second, seemingly logical design options may not effectively achieve the primary goal; increasing the portal wall elevation just to account for storm surge alone would not have increased the level of flood protection much. Wave impacts on top of the surge are

important in this coastal situation because of wave overtopping at the more exposed portal. Third, the use of the most commonly understood measure of storm strength, the Saffir-Simpson Hurricane "Category" Scale, is not particularly valuable for engineering decisions related to storm surge as there is not a one-to-one relationship between storm surge and storm "category." And finally, integrating vulnerability into decision-making will typically include some iteration or "feedback-loop" process such as the search for more effective alternative design options in this case study.

The study conducted on the Wallace Tunnel does not consider the potential impacts that future sea level rise and accompanying higher storm surge could have on the tunnel. An additional analysis of the vulnerability of the tunnel to sea level rise and accompanying storm surge is recommended to fully understand the potential risks to the tunnel. This study stemmed from an approach to modify an existing tunnel to the extent practicable and assess how it performed under storm conditions, rather than to define a design criterion and determine what would be necessary to meet that standard. For large, expensive, highly constrained projects this type of assessment might be a useful practical way to approach the problem. This can help decision makers consider a variety of questions. How much resilience can we practically build into our project? How much time or reduction of risk will a particular adaption option buy us? When does it become too expensive to modify the existing tunnel and another type of structure or route needs to be considered?

4.4.8 Shipping Pier Exposure to Storm Surge – Dock One at the McDuffie Coal Terminal

Introduction

> **Case Study Highlights**
>
> **Purpose:** To evaluate whether a shipping pier structure could be vulnerable to wave impacts from selected surge scenarios.
>
> **Approach:** A methodology by Cuomo et al (2007) was used to estimate the *quasi-static* hydraulic force of a wave colliding with the pier, and whether the pier's design was sufficient for withstanding these forces.
>
> **Findings:** According to the analysis, the pier's design is likely sufficient to withstand the modeled storm scenarios.
>
> **Viable Adaptation Options:** No specific adaptation options evaluated since the pier does not appear vulnerable to this stressor.
>
> **Other Conclusions:** Although the pier itself could withstand the modeled surges, critical equipment on and around the pier and ancillary services will need protection from any event that overtops the pier.

Piers[377] are an important linkage between maritime and land-based transportation networks. Higher storm surges resulting from rising sea levels and potential increases in hurricane intensity with climate change pose a potential threat to near shore piers and other port infrastructure. This case study explores possible future storm surge impacts on a pier at the McDuffie Coal Terminal in Mobile. This particular port facility was chosen for study because of its exposure to storm surge and the economic importance of maintaining continuity of operations. According to the Alabama State Port Authority staff, the Authority receives 50% of its revenue from the McDuffie Coal Terminal.[378] Also, if the McDuffie Coal Terminal is out of service for more than 30 days the shortage of coal can result in "brown-outs"[379] in the area.[380] This case study applies the 11-step *General Process for Transportation Facility Adaptation Assessments* to one of the piers at the McDuffie Coal Terminal as an example of how owners / operators of similar facilities might evaluate and take steps to minimize climate change and extreme weather risks. The study found that the pier studied, Dock One, was not vulnerable to the storm surge scenarios tested and no adaptation options are recommended at this time.

Application of the General Process for Transportation Facility Adaptation Assessments

Step 1 – Describe the Site Context

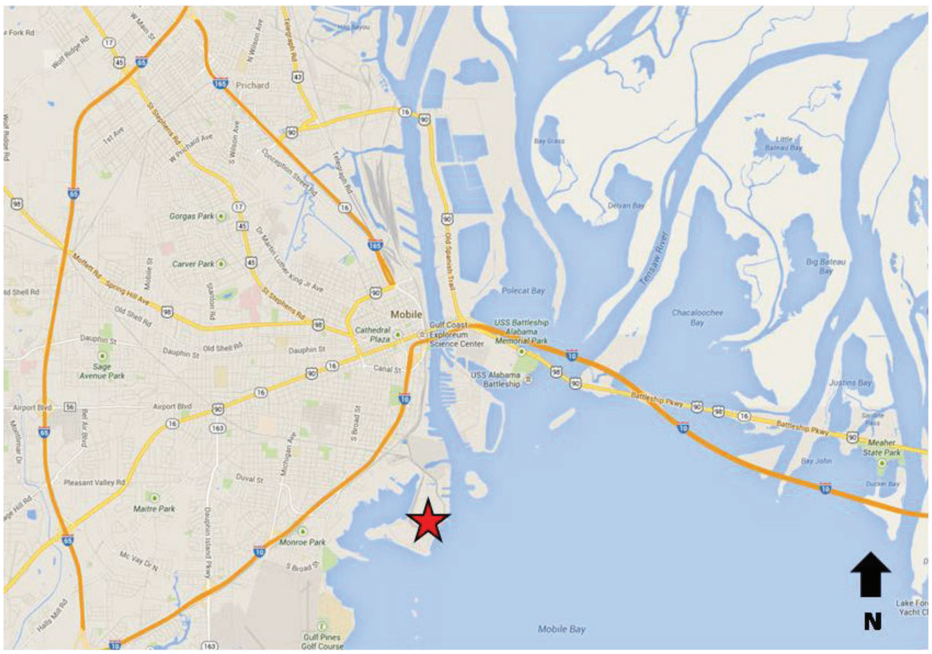
The McDuffie Coal Terminal is located on McDuffie Island, 2.5 miles (four kilometers) south of downtown Mobile (see Figure 87). The facility is one of the largest import-export coal terminals

[377] Piers, also known as docks, are elevated structures for mooring ships that connect to land and extend out into the water; they differ from wharves / quays which are also used for mooring ships but generally run parallel to the shoreline providing continuous access from the shoreline edge. The terms "pier" and "dock" are used interchangeably in practice and in this case study.
[378] Kichler, 2013
[379] A brown-out is a temporary cutback in electricity supply.
[380] Kichler, 2013

in the United States with an annual throughput capacity of 30 million tons.[381] Total import export tonnage in 2012 was 13.9 million tons.[382]

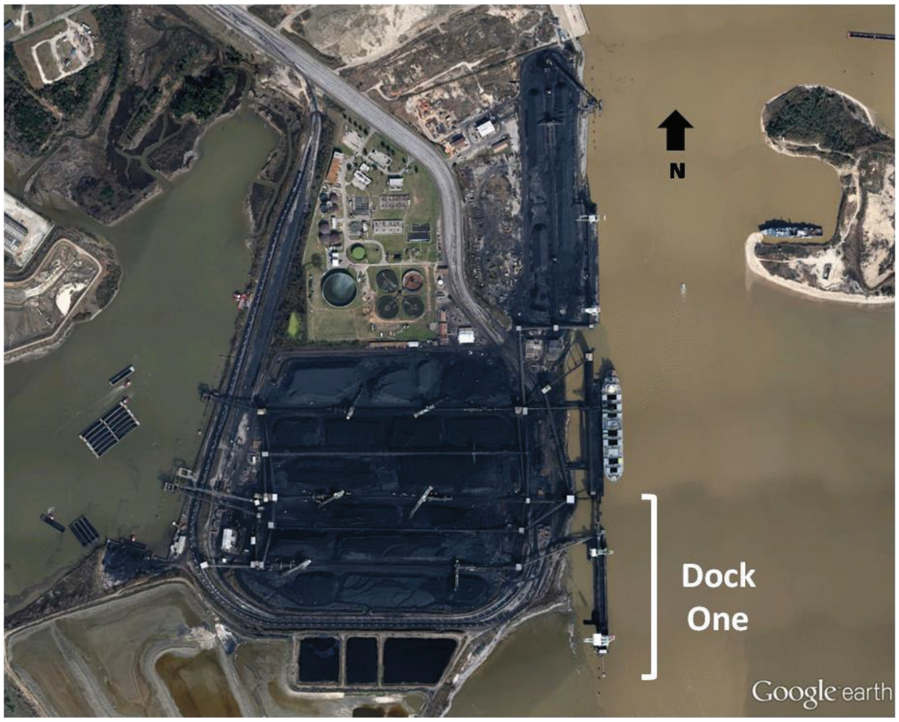
This case study will focus on one specific portion of the facility, Dock One, which is the southernmost pier at the terminal (see Figure 88). Dock One is exposed to Mobile Bay to the east and south with the main shipping channel into Mobile located just east of the berth. Dock One functions as a ship and barge loading facility for coal. Two ship loaders on the pier transfer coal from storage areas to the hulls of vessels berthed alongside the dock for distribution to domestic power plants or foreign ports.

Figure 87: Location of the McDuffie Coal Terminal[383]



[381] ASPA, 2014
[382] ASPA, 2014
[383] Source of base map: Google Maps (as modified)

Figure 88: Aerial View of the McDuffie Coal Terminal Showing Dock One[384]



Step 2 – Describe the Existing Facility

Dock One was originally constructed in 1973 and has undergone major renovations and expansions in 1994 and 2004. The dock is generally used as a single berth for larger vessels on the waterside with capability to berth multiple barges of various sizes on both the waterside and landside of the dock.

Components of Dock One include:

- The main dock itself which is 648 feet (197.5 meters) long and 62 feet (18.9 meters) wide
- A single 16 square foot (1.5 square meter) mooring dolphin[385]
- A 148 foot (45.1 meter) long by four foot (1.2 meter) wide access walkway from the pier to the mooring dolphin
- A 240 foot (73.2 meter) long by 24 foot (7.3 meter) wide two-lane access bridge from the shore to the pier.

Figure 89 shows a plan (overhead) view of the dock with all of these features marked and Figure 90 shows an oblique aerial image of the facility.

[384] Source of aerial photo: Google Earth (as modified)
[385] A mooring dolphin is a standalone man-made structure above the water level that ships can tie up to. Dolphins typically consist of a series of vertical wood, steel, or concrete piles driven into the seabed that are tied together at the top by wire rope or a concrete or steel cap.

Figure 89: Aerial View of Dock One[386]

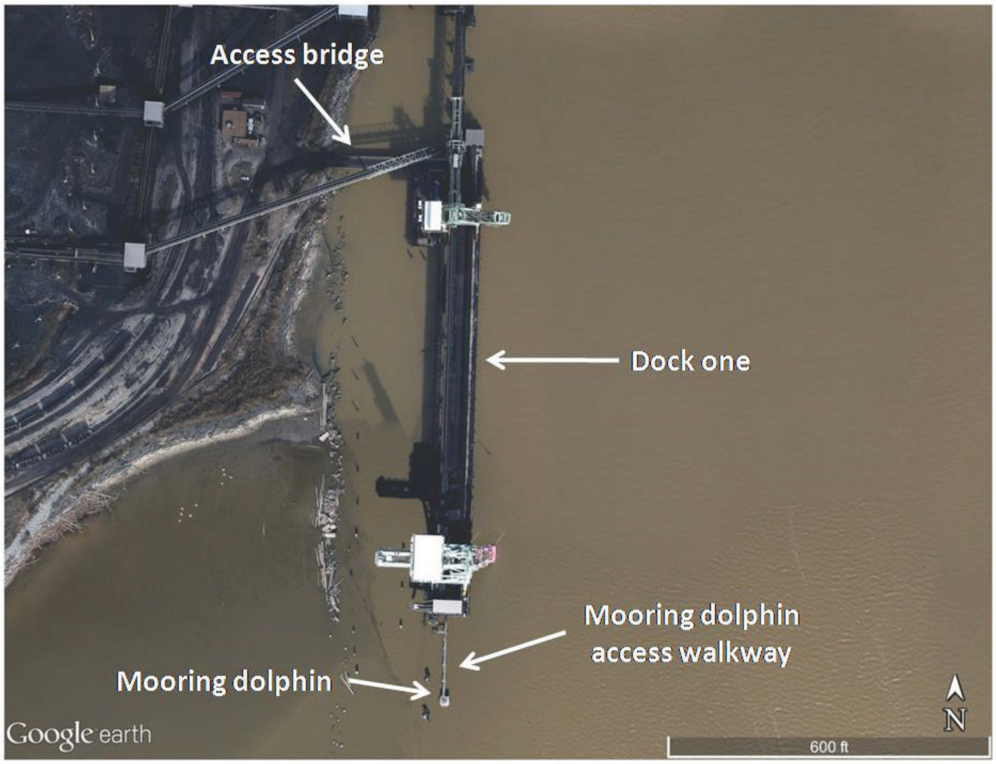
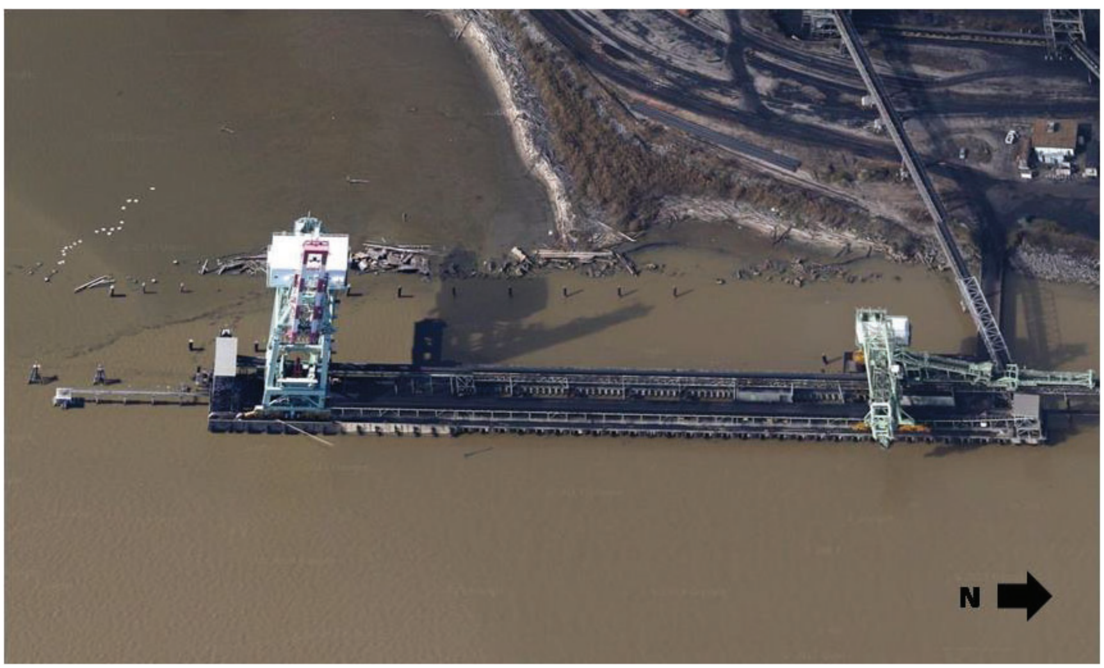


Figure 90: Oblique Aerial Image of Dock One[387]



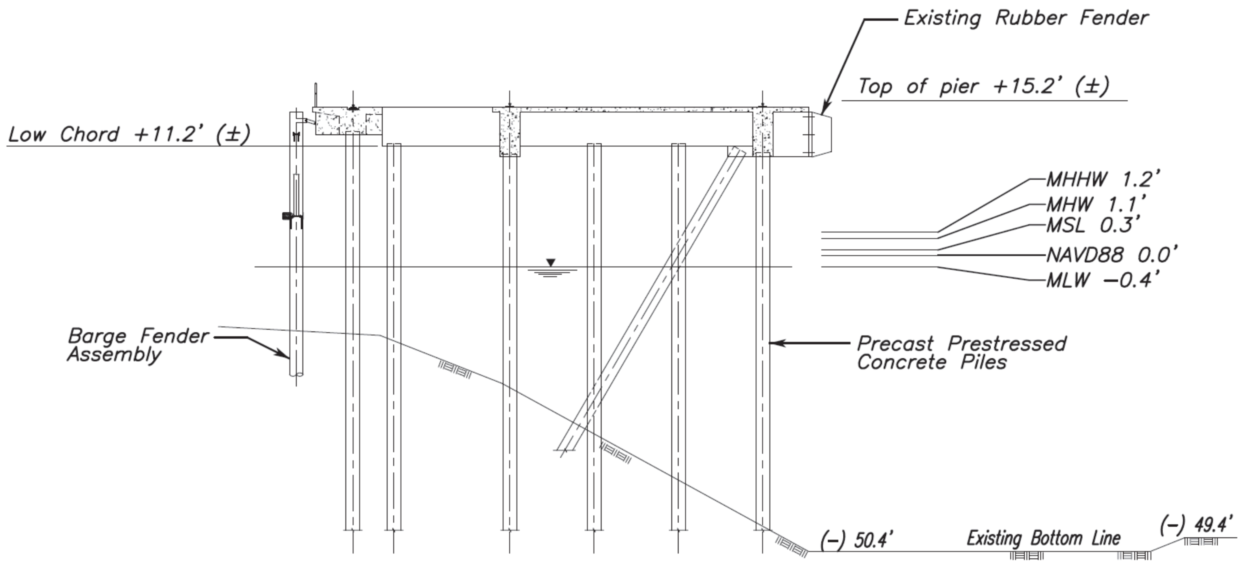
[386] Source of aerial photo: Google Earth (as modified)
[387] Source of aerial photo: Google Maps (as modified)

The dock's construction consists of a cast-in-place reinforced concrete deck supported by cast-in-place reinforced concrete beams supported by precast prestressed concrete piles.[388] The top of pier elevation is approximately 15.2 feet (4.6 meters)[389] with a low chord elevation (bottom of cap beam) at approximately 11.2 feet (3.4 meters). Mean Low Water[390] (MLW) is at -0.4 feet (-0.1 meters), Mean Sea Level[391] (MSL) is at 0.3 feet (0.1 meters), Mean High Water[392] (MHW) is at 1.1 feet (0.3 meters), and Mean Higher High Water[393] (MHHW) is at 1.2 feet (0.4 meters). Figure 91 provides a typical section for the dock showing each of these water elevations.

Industrial piers like the one at McDuffie are designed for very large loads. Dock One is designed for crane wheels loads of 27,000 pounds per linear foot (40,180.4 kilograms per linear meter) of rail, deck uniform live loads[394] of 750 pounds per square foot (3,661.9 kilograms per square meter), and concentrated loads[395] of 100,000 pounds (45,392 kilograms). Loads from ship impact berthing and mooring lines are very large as well. The mooring bollards[396] at Dock One are located at 60 foot (18.3 meter) intervals and rated for 200,000 pounds (90,718.5 kilograms) each. The fender system[397] elements designed to resist berthing loads are spaced at 20 foot (6.1 meter) centers and deliver a reaction to the dock structure of 190,000 pounds (86,182.6 kilograms). These lateral loads are unique to piers and thereby require them to have substantial lateral load force resisting systems. As a result of these loads, piers tend to be very robust in nature when compared to other structures.

[388] Piles are the vertical support members extending from the deck of the pier structure to the seabed.
[389] All elevations in this study are with respect to the North American Vertical Datum of 1988 (NAVD88).
[390] Mean low water is the average of all low tide elevations during the day over the current National Tidal Datum Epoch. The tidal epoch is the specific 19-year period over which NOAA uses to obtain observations that are used to develop tidal statistics.
[391] Mean sea level is the average of the water elevations recorded at each hour of the day over the current National Tidal Datum Epoch.
[392] Mean high water is the average of all high tide elevations during the day over the current National Tidal Datum Epoch.
[393] Mean higher high water is the average elevation of the highest daily high tide over the current National Tidal Datum Epoch.
[394] Deck uniform live loads refer to design loads of uniform force applied to a large area.
[395] Concentrated loads refer to a singular design load applied at a single location.
[396] Mooring bollards are fixtures mounted to ship berths for attaching the mooring lines and ropes used to hold ships against the berth.
[397] A fender system separates a ship from a dock structure and is used as an energy absorbing cushion.

Figure 91: Typical Section of Dock One



The mooring dolphin is cast-in-place concrete supported by precast prestressed concrete piles. The mooring dolphin has a top of deck elevation of 14 feet (4.3 meters) and a low chord elevation (the soffit / underside) of 11.2 feet (3.4 meters). The mooring dolphin access walkway is constructed of a concrete topping slab over hollow core prestressed deck slabs supported by cast-in-place reinforced concrete pile caps supported by precast prestressed concrete piles. The top of the access walkway matches the top of deck elevation of the pier at approximately 15.2 feet (4.6 meters) with a low chord elevation (bottom of cap beam) at approximately 13.2 feet (four meters).

The two-lane access bridge is a cast-in-place reinforced concrete deck slab supported by precast prestressed girders. The girders are supported by cast-in-place reinforced concrete pile caps which in turn are supported by precast prestressed concrete piles. The top of the deck elevation of the two-lane access bridge varies from 9.6 feet on the landside (2.9 meters) to 15.2 feet on the pier (4.6 meters) with a low chord elevation (bottom of cap beam) varying between 2.4 feet (0.7 meters) and eight feet (2.4 meters). At 9.6 feet (2.9 meters), the surrounding land is actually lower than the pier itself such that the access bridge ramps upward 5.6 feet (1.7 meters) to reach the deck of the pier.

The coal loading equipment located on Dock One, critical to its operation, are two ship loaders and a series of coal conveyor structures. The conveyors feed coal to the ship loaders which are run by an operator. The operator controls the loading of coal into the vessels berthed at Dock One.

It should be noted that this study focuses only on the performance of the Dock One pier structure itself: it does not examine the storm effects on the mooring dolphin, mooring dolphin access

walkway, access bridge (refer to Section 4.4.6 of this document for a case study showing how to conduct an analysis of storm surge impacts on a bridge), and dock equipment and infrastructure (cranes, ship loaders, conveyors, buildings, etc.). While typically the dock structures at industrial facilities survive storm events, the same cannot always be said about the equipment and infrastructure. Additionally, the loadings caused by any possible equipment damage are also not factored into the assessment of the stresses placed on the pier. A full analysis of a port facility should consider all components of port operations including equipment, storage facilities, and access routes. This type of broad analysis, however, was beyond the scope of this case study.

When conducting climate change analyses of existing pier facilities, it is also recommended that a thorough understanding of the facility's condition be factored into the analysis. Information such as condition assessments, load ratings, and structural inspections should be consulted and, if not available, new inspections of the facility should be undertaken. Unfortunately, information on the existing condition of Dock One was not available for this case study and resources were not available to conduct new inspections. Thus, for the purposes of this study, Dock One is considered to be in "as new" condition and has been evaluated based on information found in construction drawings of the existing facility. Components that may have required repair or replacement are assumed to have been maintained in such a way that they perform as originally intended.

Step 3 – Identify Climate Stressors That May Impact Infrastructure Components

Wind, sea level rise, and storm surge are the most critical environmental variables relating to pier design that climate change might affect. This study focuses specifically on the storm surge component with wind and sea level considered to the extent they affect potential future surge elevations.

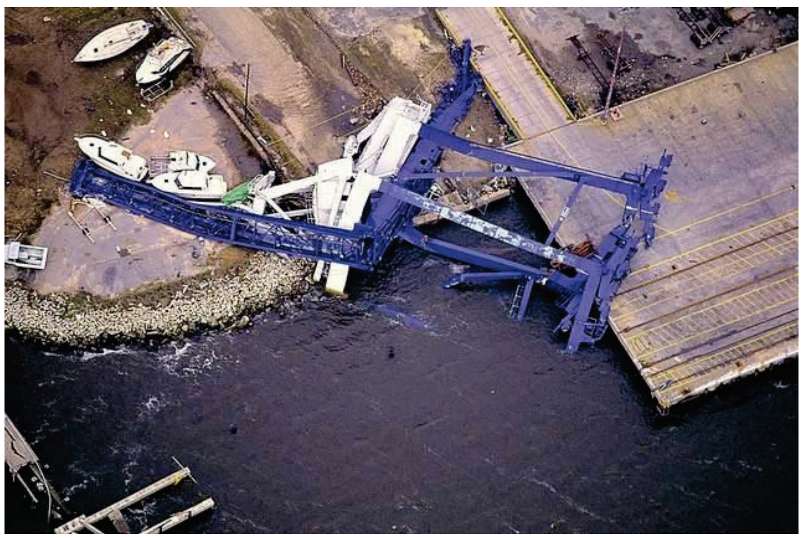
That said, it is important to note that with regards to pier design, "As a general rule, horizontal design loads on vessel berthing structures are governed by vessel berthing[398] and mooring loads,[399] or, sometimes, seismic[400]" loads.[401] "Wind, wave, and current forces acting directly on the structure usually can be neglected."[402] Near shore piers such as Dock One are first and foremost designed to perform the facility's primary function; the loading and unloading of ships. Storm surge is given consideration after the operational parameters of keeping the facility functioning through seasonal tide ranges are established. *There are currently no code requirements that impact the design of facilities such as Dock One with regards to storm surge*. The reasoning for this is that berthing and mooring loads are typically much greater than the loads caused by storm conditions and, historically, the survivability of these types of structures has been very high during storms. Such analysis should be revisited with an eye to future

[398] Berthing loads are those incurred when a vessel impacts a berth upon approach.
[399] Mooring loads are those loads applied from vessel tie lines to the mooring hardware located on the pier deck.
[400] Seismic loads occur during earthquakes.
[401] Gaythwaite, 2004
[402] Gaythwaite, 2004

changes in storm surge and sea levels. This analysis represents a first step in that direction. If it is determined that future events could make piers more vulnerable, then it would be important to consider climate effects in pier design.

Hurricane Hugo which struck Charleston, South Carolina in 1989 provides an example of the high survivability of pier structures in storms. The hurricane produced tremendous wind and storm surge damage; in fact, Hugo produced some of the highest storm tide heights ever recorded along the U.S. East Coast at the time. The damage to the Port of Charleston infrastructure was significant; however, the performance of the pier and wharf structures in the face of high wind and record surge was remarkable. Figure 92 below shows the after effects of a wind and storm surge combination strong enough to have toppled the container handling gantry crane. However, the dock structure itself and two-lane access ramp, shown at the top and right of the picture, survived intact.

Figure 92: Columbus Street Terminal in Charleston, SC, After Hurricane Hugo[403]



Closer to Mobile, The American Society of Engineers (ASCE) conducted post Hurricane Katrina assessments of ports, harbors, and marine facilities and published their findings in a book titled *Hurricane Katrina Damage Assessment: Louisiana, Alabama, and Mississippi Ports and Coasts*.[404] It contains numerous detailed descriptions of damage and overall performance throughout the region including that of piers and wharves similar to Dock One. Most all of these structures sustained very little structural damage; even those closer to where the storm made landfall. The McDuffie Island complex was investigated specifically and the minor structural damage noted in the investigation was due to several vessels being tied up alongside during the hurricane including a large bulk vessel laden with coal. Note that it is generally not an acceptable

[403] Spain, 1989
[404] Curtis, 2007

procedure to allow vessels to be moored alongside piers during storm events. It is the policy of the Alabama State Port Authority to request all ships to sail during hurricane events.[405]

Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes

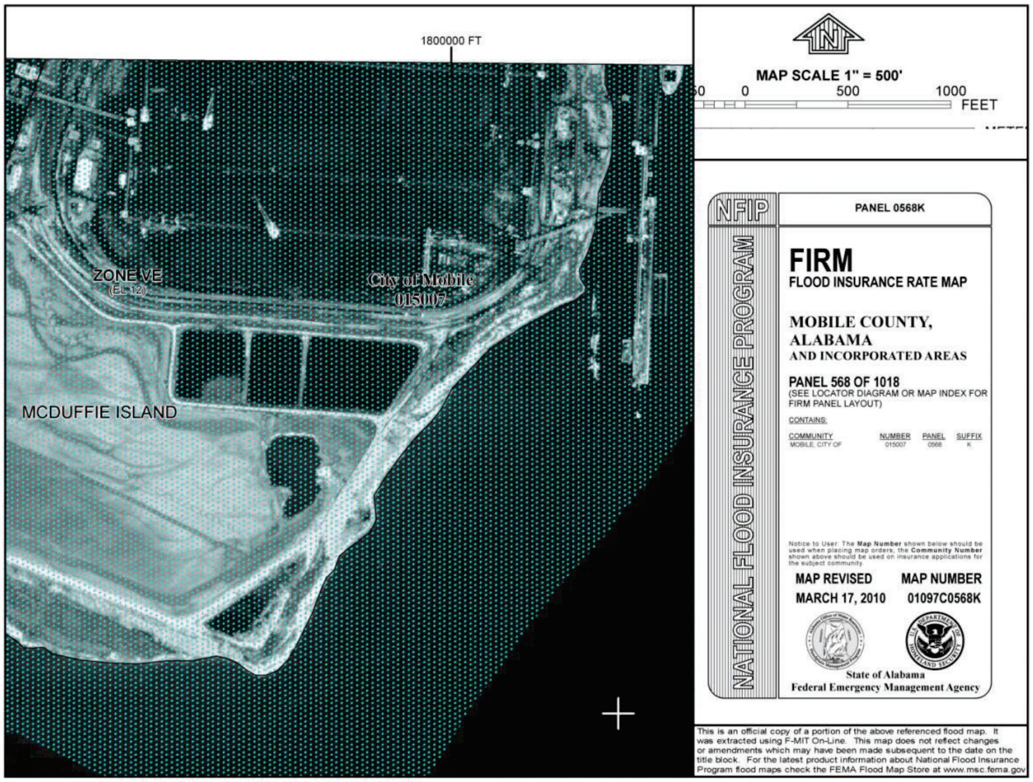
As noted in Step 3, major industrial piers like Dock One are typically designed not for a particular return period storm but first and foremost for their functional purpose of berthing ships since such design loads tend to be controlling. Nonetheless, while it is not required by code, it is common practice for pier designers to check back to the 100-year coastal flood elevation (the one percent annual probability storm) to make sure it does not overtop the pier and jeopardize any equipment on the structure.

FEMA Flood Insurance Studies have historically been the authoritative source of this information for current conditions in coastal areas of the United States. As an example of these data sets, a portion of the Flood Insurance Rate Map (FIRM) that includes Dock One at McDuffie Terminal is shown in Figure 93. As one can see, the entire southern end of the McDuffie Terminal is expected to be inundated during a 100-year event. The base flood elevation[406] of this storm at Dock One is 12 feet (3.7 meters).[407] FEMA designates V and A zones within the coastal flood zone to delineate different hazard levels associated with the flood.[408] The V zone denotes "Coastal High Hazard Areas" with wave heights in excess of three feet whereas "Coastal A Zones" denote areas where wave heights are less than three feet. As shown in Figure 93, McDuffie Terminal lies within the coastal high hazard area (VE zone) with the "E" denoting that a detailed study was conducted and that base flood elevations and depths are available. FEMA (2014b) provides a listing and definition of all the possible zone designations that may occur within the V zone (e.g., V, VE and V1-30 zone designations) and A zones.

[405] Kichler, 2013
[406] The term "base flood" refers to the 100-year (one percent annual probability) storm. Thus, the base flood elevation is the elevation that the floodwaters are expected to reach during the 100-year storm.
[407] FEMA, 2010c
[408] See FEMA, 2014a for more information.

FHWA002893

Figure 93: FEMA Flood Insurance Rate Map Showing the 100-Year Flood Elevation for McDuffie Terminal and Dock One[409]



In addition to FEMA, U.S. Army Corps of Engineers (2002) provides a wide range of data sources (including wind, waves, water levels and other information) useful for the design of particular facilities within ports (e.g., revetments, floating docks, and other assets that should not be inundated during floods).

As discussed in Step 4 of Section 4.4.4 , it is difficult to develop a future 100-year flood elevation that considers climate change impacts on sea levels and storm tracks, intensities, and frequencies. Given this, a scenarios approach was taken to the surge analysis whereby the track and intensity of historical storms in the region were changed along with sea levels to indicate possible future storm threats. The following three storm surge scenarios were considered for this adaptation assessment:

- **Hurricane Katrina Base Case Scenario**: This scenario represents the surge conditions that actually occurred in Mobile with Hurricane Katrina making landfall at the Louisiana-Mississippi border. The effects of Hurricane Katrina on the Mobile area were not as severe as they were at the Louisiana-Mississippi border.
- **Hurricane Katrina Shifted Scenario**: This scenario estimates the surge levels that would occur if Hurricane Katrina's path was shifted east to make landfall in Mobile.

[409] FEMA, 2010c. Note: The elevations shown are in NAVD88.

- **Hurricane Katrina Shifted + Intensified + Sea Level Rise (SLR) Scenario**: This scenario estimates the surge levels that would occur if Hurricane Katrina was shifted, intensified with stronger winds due to climate change, and came on top of 2.5 feet (0.8 meters) of sea level rise.

A more detailed description of each scenario and how it was developed can be found in Section 4.4.4 of this document (under Step 4) and in the *Climate Variability and Change in Mobile, Alabama* report.[410]

Table 51 shows the storm surge elevations under each of the three scenarios developed along with the current FEMA base flood elevation. The model results shown in Table 51 were obtained from the models at the south end of Dock One offshore in the navigation channel. The model domain resolution did not allow precise replication of the deep berths at the McDuffie Terminal and, as a result, the depths in the model near the dock are somewhat less than actual conditions. As such, the current was somewhat less so the model results were taken slightly to the east of the dock where the modeled depths were the same as actual conditions. Although the currents are relatively moderate, they do increase significantly to the north along McDuffie Terminal with the maximum modeled current, 5.9 knots (10.9 kilometers per hour), occurring at the north end of the McDuffie Terminal for the Hurricane Katrina Base Case Scenario.

Table 51: Storm Surge Analysis Results for Dock One at McDuffie Terminal[411]

Storm Surge Scenario	ADCIRC Hydrodynamic Model Results			STWAVE Wave Model Results		
	Water Surface Elevation Feet (m)	Sustained Wind Speed mph (kph)	Depth Averaged Current Knots (kph)	Wave Height[412] Feet (m)	Peak Wave Period (sec)	Wave Direction[413] (Compass Degrees)
Hurricane Katrina Base Case	12.4 (3.8)	75 (120.7)	2.9 (5.4)	5.6 (1.7)	7.1	356
Hurricane Katrina Shifted	19.7 (6.0)	106 (170.6)	2.9 (5.4)	6.2 (1.9)	7.7	354
Hurricane Katrina Shifted + Intensified + SLR	24.6 (7.5)	112 (180.2)	2.3 (4.3)	4.0 (1.2)	7.6	1

Step 5 – Assess Performance of the Existing Facility

As an interconnected and interdependent system, the performance of the existing pier is a sum total of the performance of its various components. This study focuses on assessing the

[410] USDOT, 2012
[411] The FEMA base flood elevation is 12 feet (3.7 meters) (FEMA, 2010c).
[412] This value represents the zeroth moment wave height as reported by the STWAVE Model and in deep water is equivalent to the more commonly used term "significant wave height" which is the average of the highest one third of waves in a random wave field
[413] Wave direction values refer to compass directions. For example, waves at zero degrees are traveling north and waves at 270 degrees are traveling west.

survivability and performance of the Dock One main pier under each of the three storm surge scenarios.

The main pier itself has significant mass and strength which aid in resisting both wave uplift and lateral loads. Additionally, the longitudinal (long axis) orientation of the pier is coincident with the fetch[414] and predicted wave direction. That is to say that the pier is not broadside to the prevailing wave front but rather the narrow end of the pier with the smallest profile faces the approaching waves. This minimizes both wave and current influence area on the structure since the surface area of pier elements exposed to wave load is minimal. For these reasons, it is expected that the pier will survive most storm events.

To confirm these expectations, validate the observations of the actual Katrina event, and provide an example of how one might quantify a pier's vulnerability to surge, an attempt was made to determine actual loads on the pier and compare them to its design capacity. This was done by conducting a strength analysis of the Dock One pier structure and comparing the results to surge-related loads derived from a European study by Cuomo et al. (2007) titled *Wave-in-Deck loads on Exposed Jetties*.

During a major storm event, three main forces should be considered for analysis of a pier:

- **The dead weight of the structure itself**
- **The buoyancy of the pier as a function of the water height:** As the wave rises, the buoyancy force on the structure is a combination of the water displaced by the structure as well as the water displaced by entrapped air beneath the structure
- **The hydraulic force of the wave / water colliding with the pier:** This includes the following three primary hydraulic loadings:
  - ***Impulsive***: The impulsive loading is the initial impact of the wave on the pier in which the pier experiences the highest force over the shortest duration
  - ***Quasi-static***: The quasi-static loading is longer and consists of the wave's pulsing action in addition to the buoyancy force of the sea water
  - ***Suction***: After a wave passes, the water recedes creating a suction (downward) force on the deck

For the analysis of Dock One, the methodology in the report written by Cuomo et al (2007) was implemented to determine the quasi-static loads applied to the pier from the wave. Impulsive and suction loadings were not considered in this analysis.

With regards to impulsive loads, the report states that, "It must be stressed that impulsive loads measured during physical model tests have relatively short rise times…that might fall within the range of the natural periods of vibration of the prototype structures."[415] Similarly, it goes on to

[414] Fetch refers to the area over water where the wind is unobstructed with fairly uniform speed and direction.
[415] Cuomo, Tirindelli, and Allsop, 2007

state that, "when significant impulsive loads are expected to act on the suspended deck structure, the evaluation of the impulsive load to be used in design analysis must account for the dynamics of the prototype structure."[416]

It is estimated that the wave impact to the Dock One structure has a duration of 0.01 to 0.1 seconds for a storm surge of this magnitude. In order to assess the capability of a particular structure to resist high impact short duration loads, structural computer modeling and analysis is required to determine dynamic response of the structure and load distribution. Structural modeling could perhaps account for the inertia, dynamic response, and deflection / displacement of the dock when exposed to the energy of an impulsive load. This analysis is, however, well beyond the scope for this study. Additionally, the primary focus and main results of the paper are on the determination of the quasi-static loading. For these reasons, the impulsive load was not considered. The significance of not considering impulsive load on the pier is difficult to determine because it is not apparent how the load affects the structure. Impulsive loads are extremely large, two and three times that of static loads, however their short duration and limited contact area reduce their influence on required design strength.

With regards to the suction load, it is very small relative to the quasi-static load and acts in the same direction (downward) as the design loads. For these reasons, suction load is not considered in this analysis. A full assessment of an actual pier project should consider both impulsive and suction loads in the analysis.

The Cuomo et al. (2007) formulas for calculating the quasi-static wave force were derived from physical model tests on a 1:25 scaled model of a pier similar in construction to Dock One fitted with strain gauges[417] at different locations. Due to the empirical nature of the formula, it is assumed that it incorporates all the hydraulic forces (quasi-static, buoyancy, etc.) acting on the pier during a wave event. For this reason, additional buoyancy was not added to the upward force calculated from the Cuomo et al. (2007) equation used for determining load on the members of Dock One. Likewise, it could be assumed that the empirical data gathered during testing would have included the dead weight of the scaled model acting in the opposite direction of the quasi-static load. For this reason, a conservative approach was taken by not using the dead weight of the structure to resist wave uplift loads.

<u>Hurricane Katrina Base Case Scenario</u>

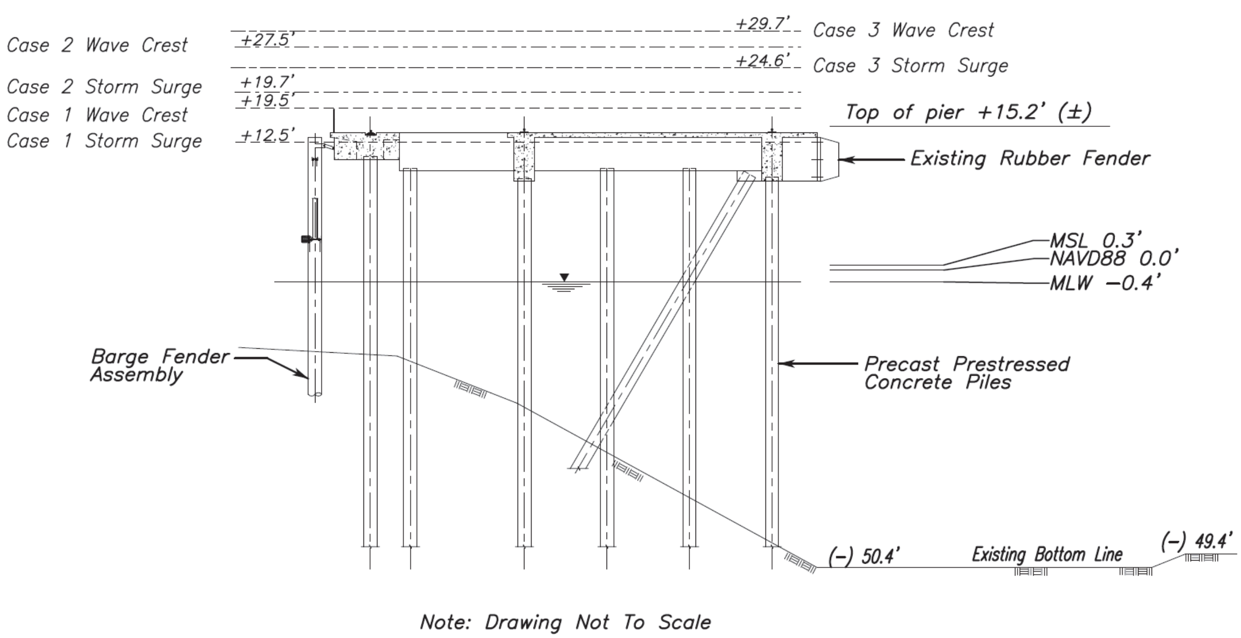
The Hurricane Katrina Base Case Scenario results in a storm surge elevation of 12.5 feet (3.8 meters) at Dock One; below the top of pier elevation of approximately 15.2 feet (4.6 meters) and above low chord elevation (bottom of cap beam) of approximately 11.2 feet (3.4 meters). The storm also entails an average significant wave height crest elevation of 19.5 feet (5.9 meters);

[416] Cuomo et al., 2007
[417] A strain gauge is a device used to measure strain on an object. The results are used to determine how that object is performing under applied loads.

high enough to overtop the pier, mooring dolphin, and mooring dolphin access walkway. Figure 94 illustrates the surge and wave crest elevations for this scenario and the other two surge scenarios.

Waves during the Hurricane Katrina Base Case Scenario break above all parts of the structure as well as creating uplift forces from the underside of the pier deck. This is the scenario that potentially causes the most damage to a structure of this type because the other two scenarios (the Hurricane Katrina Shifted and Hurricane Katrina Shifted + Intensified + SLR Scenarios) would cause the pier to be inundated by the surge, resulting in less force being applied to the structure from waves. Should a condition like this occur over a prolonged period of time, the cyclical nature of wave loading might lead to structural fatigue potentially having a damaging impact on key elements of the pier. Analysis of fatigue may be worth considering on an actual project, however, such an analysis was well beyond the scope of this study.

Figure 94: Typical Section at Dock One Showing Storm Surge and Wave Crest Elevations for the Surge Scenarios[418]



As noted in Step 2, the main section of Dock One at the McDuffie Coal Terminal is a cast-in-place reinforced concrete structure with three main longitudinal beams and corresponding transverse beams supported by precast prestressed concrete piles. The pile supported transverse beam is referred to as the cap beam. Two of the three longitudinal beams support the rails for the crane. These are referred to as the waterside and landside rail beams. The third longitudinal beam

[418] Case 1 refers to the Hurricane Katrina Base Case Scenario, Case 2 is the Hurricane Katrina Shifted Scenario, and Case 3 is the Hurricane Katrina Shifted + Intensified + SLR Scenario.

is the landside fascia beam.[419] The deck between the rail beams is referred to as the rail bay deck and has a thickness of 18 inches (45.7 centimeters). The exterior bay (between the rail and west fascia beam) is referred to as the landside bay deck and is 14 inches (35.6 centimeters) thick.

Each of these pier elements was analyzed individually using the Cuomo et al (2007) methodology in an attempt to determine its structural strength (shear[420] and moment capacity [421]) during the Hurricane Katrina Base Case Scenario.

For this analysis, quasi-static loads were applied to each element of the pier. A load factor[422] of 1.75[423] was applied to the quasi-static loads. Table 52 shows the factored quasi-static forces, the resulting factored moment and factored shear forces, and the moment and shear capacity of each element. Comparison of the results reveals that the factored moment and shear forces produced by the quasi-static load do not exceed the moment and shear capacities of any of the individual pier elements. Therefore, the pier is able to withstand the force from a wave for the Hurricane Katrina Base Case Scenario.

Hurricane Katrina Shifted Scenario

The Hurricane Katrina Shifted Scenario produces a storm surge elevation of 19.7 feet (six meters) at Dock One and an average significant wave height crest elevation of 27.5 feet (8.4 meters). With Dock One having a top deck elevation of about15.2 feet (4.6 meters), this scenario would put about 4.5 feet (1.4 meters) of storm surge over the top of the pier deck (see Figure 94).

The effects of this scenario before it overtakes the pier would be similar to the Hurricane Katrina Base Case Scenario before it overtakes the pier. Once submerged, the structure itself is protected from the environmental loads occurring above the storm surge elevation. The key is the ability of the structure to withstand the wave load on the superstructure through the transition from above water to below storm surge. The duration of this transition also has an effect. A surge that comes in quickly has much less impact than one that is prolonged thereby providing extended exposure to wave action. Quantifying the duration of exposure required to fail an element is a very subjective and dynamic problem that may need to be considered on some studies. However, for this analysis, given that the pier is likely to survive the longer duration wave exposure of the Hurricane Katrina Base Case Scenario, such an analysis is not necessary.

[419] A fascia beam is a beam at the face or perimeter of a structure.
[420] Shear capacity is the strength of a material or component against the type of yield or structural failure where the material or component fails through shearing.
[421] Moment Capacity or flexural strength represents the highest stress experienced within a material under bending at its moment of rupture.
[422] Load factors may be thought of as safety factors that are applied to the loads.
[423] A factor of 1.75 is recommended for wave loads in *Guide Specifications for Bridges Vulnerable to Coastal Storms* (AASHTO, 2008).

Table 52: Dock One Strength Analysis Results

Pier Element	Quasi-Static Load kips/ft (kN/m)	Moment		Shear	
		Factored Moment kips·ft (kN·m)	Moment Capacity kips·ft (kN·m)	Factored Shear kips (kilonewtons)	Shear Capacity kips (kilonewtons)
Landside Bay Deck	0.7 (10.2)	15.9 (21.5)	49.3 (66.8)	4.7 (20.9)	13.0 (57.9)
Rail Bay Deck	0.7 (10.2)	23.7 (32.1)	70.7 (95.9)	5.7 (25.6)	17.6 (78.5)
Waterside Rail Beam	1.8 (26.1)	4.9 (6.6)	959.6 (1,301.1)	4.2 (18.6)	254.7 (1,132.9)
Landside Rail Beam	1.8 (26.1)	4.9 (6.6)	959.6 (1,301.1)	4.2 (18.6)	254.7 (1,132.9)
Landside Fascia Beam	1.8 (26.1)	60.9 (82.6)	1,183.3 (1,604.4)	14.8 (65.7)	305.0 (1,356.9)
Cap Beam	1.8 (26.1)	40.8 (55.3)	1,934.3 (2,622.6)	12.1 (53.7)	305.0 (1,356.9)

Thus, given available data, the pier is likely to survive the Hurricane Katrina Shifted Scenario. Although it was not part of the analysis, it is likely that the equipment, machinery, buildings, etc. that are mounted to the pier deck will be extremely vulnerable to the storm surge in this scenario. Debris, saltwater, and wave impacts could possibly take these items off line.

Hurricane Katrina Shifted + Intensified + SLR Scenario

The third surge scenario, Hurricane Katrina Shifted + Intensified + SLR, produces a storm surge elevation of 24.6 feet (7.5 meters) and an average significant wave height crest elevation of 29.7 feet (9.1 meters). In terms of storm surge, with Dock One having a top deck elevation of about 15.2 feet (4.6 meters), this scenario would put over nine feet (2.7 meters) of surge over the top of the pier deck (see Figure 94).

As previously stated, the Hurricane Katrina Base Case Scenario is viewed as the worst case due to the fact that it has waves breaking on the pier. The effects of that scenario would be similar to the Hurricane Katrina Shifted Scenario before it overtakes the pier. Once submerged, the structure itself is protected from the environmental loads occurring above the storm surge elevation. Thus, given available data, the pier is expected to survive the Hurricane Katrina Shifted + Intensified + SLR Scenario. However, as with the previous scenario, additional consideration should be given to the vulnerability of the equipment on the pier deck to the surge.

Step 6 – Identify Adaptation Option(s)

As noted in Step 5, the various pier components studied are expected to adequately survive all three storm surge scenarios, including wave forces on the structure and uplift forces beneath the structure. Thus, no adaptive design options are required for the pier components analyzed. Although not studied here, additional consideration should be given to ways to best protect the vulnerable equipment investment on the pier so that after the storm passes there is minimal downtime required to get back online. The access bridge and mooring dolphin access walkway may reasonably be presumed to be the most vulnerable of the facility components. Consideration may be given to strengthening these elements or perhaps making them easily removable so that they may be properly stowed before the onset of a storm event.

Step 7 – Assess Performance of the Adaptation Option(s)

If adaptive actions were needed for the pier components analyzed, this step would entail assessing the performance of each adaptive action against each of the surge scenarios.

Step 8 – Conduct an Economic Analysis

If adaptation options were required for the pier components analyzed, an economic analysis should be conducted to determine each adaptation option’s cost-effectiveness under each of the surge scenarios. See Section 4.4.1 for an example of how an economic analysis was applied to a culvert exposed to changes in precipitation due to climate change.

Step 9 – Evaluate Additional Decision-Making Considerations

As there are no adaptation actions required for the pier components analyzed, no additional decision-making considerations are applicable. If adaptation was required, this step might entail consideration of broader project sustainability, project feasibility, practicality, ongoing maintenance needs, funding availability, and, very importantly for the pier, stakeholders’ tolerance for risk and service interruption. The latter is a key consideration when interpreting the results of any economic analysis conducted for Step 8. Also, as noted previously, the possibility of debris impacting the structure should be a consideration and, in cases where there is a high potential for large damaging debris, this might be a factor in choosing a stronger adaptation option.

Step 10 – Select a Course of Action

The recommended course of action is to take no adaptive actions to the pier at this time.

Step 11 – Plan and Conduct Ongoing Activities

For Dock One and similar facilities, owners should establish regular structural inspection intervals in order to maintain “as-new” condition. The ability of a structure to function fully as intended will go a long way in resisting the occasional overload, load reversal, or extreme environmental load. Intervals of one, three, or five years at most are standard throughout the industry with specific inspections occurring as needed, usually after a specific event. These

regular inspections would also provide the opportunity to inspect the connections of access bridges and walkways and determine if they are capable of withstanding storm surge and wave loading.

Conclusions

Dock One at the McDuffie Coal Terminal was analyzed against current climate and three potential surge scenarios to determine the performance and survivability of the dock against environmental loads. Dock One had survived Hurricane Katrina with no damage and it was determined that the likelihood of this structure to perform well under all three climate scenarios is very good. The continued policy that no ships remained moored alongside the pier is critical to limit or eliminate damage to the pier during a storm event as well as limit or eliminate the potential of the ships themselves or pier appurtenances from becoming large damaging debris.

The key take away from this case study is that industrial piers like Dock One are designed for very large loads and tend to be very robust in nature when compared to other structures. Historically the survivability of these structures is very high and, given the general dismissal of storm environmental loads on the structure itself due to their relative insignificance compared to the operational design loads, in depth analysis has seldom been warranted in traditional practice. This might need to be reevaluated with the possibility of stronger storms associated with climate change in at least some circumstances. On the other hand, dock equipment and infrastructure (cranes, buildings, etc.) will become increasingly vulnerable to higher surge levels as climate changes: a pier structure that survives serves little purpose if the cranes necessitating its existence are damaged and off line. General sea level rise with climate change may also present a challenge to continued operations at these facilities. Therefore, port authorities should focus their resiliency attention on things like equipment and buildings that are not so heavily built and have been seen to suffer damage in storms.

Historical survivability of pier structures is also the primary reason that design guidance for storm surge loads has not been fully developed. While loads were extrapolated from the Cuomo et al. (2007) research document in order to develop some type of comparative analysis, the correctness and applicability to the Dock One pier can be challenged due to the pure empirical nature of the testing scenarios used in developing the load equations. Additional research and testing is necessary in order to establish a procedure for both load development and structural analysis that can be adopted universally for structures of this type with varying configurations. The culmination of this effort would result in a credible design guide that would be made available as a resource to pier designers. The limited guidance available should continue to be vetted by comparing the theoretical results with actual events.

4.4.9 Pavement Mix Design Exposure to Temperature Changes

Introduction

Roadway pavement, particularly newly installed pavement, can be sensitive to increased temperatures and loads causing distortions[424] that turn into "ruts" or crack when various forces combine. Pavement rutting[425] and cracks can slow traffic and freight movement, damage vehicles, and potentially affect vehicle control in some cases.

> **Case Study Highlights**
>
> **Purpose:** Evaluate potential impacts to pavement due to projected increases in temperature.
>
> **Approach:** The asphalt concrete pavement mix currently used in Mobile was evaluated against the projected future temperatures by converting the ambient temperatures to pavement temperature.
>
> **Findings:** The current pavement binders used in Mobile are sufficient for the projected temperatures analyzed. However, the current pavement mix does come close to being vulnerable under the more severe projections analyzed.
>
> **Viable Adaptation Options (in other areas that could be vulnerable):**
>
> - For AC pavement: Use different or thicker pavement
> - For PCC pavement: Change the frequency or type of maintenance, or installation methods
>
> **Other Conclusions:** It may be beneficial to use either projected temperatures or updated historical temperatures when selecting pavement binders, rather than relying on historical temperature records.

To date, relatively little research has been completed to investigate the potential impacts of climate change on pavement infrastructure in the United States. This is true despite the dependence of many states' economic and social activity on roadway infrastructure. A review of pavement engineering practices, models, and approaches to monitor, assess, and predict pavement performance reveals that climate, and therefore climate change, is an important consideration in at least two deterioration processes: rutting in Asphalt Concrete (AC)[426] pavements and cracking in Portland Cement Concrete (PCC) pavements.

As with other infrastructure, the fundamental concern related to climate change in pavement infrastructure is the potential for premature design failure. Current and past designs have generally assumed a static climate whose variability can be adequately determined from records of weather conditions that normally span less than 30 years and often less than 10 years. The possibility of climate change challenges this assumption and raises the prospects that the frequency, duration, or severity of both rutting and cracking may be altered which could lead to premature deterioration. This is the case because most AC pavements are designed for a 20 year design life; long enough to potentially be subjected to changing climate conditions. PCC pavements have an even longer lifespan, upwards of 40 years, which is long enough to be subjected to significant changing climate conditions. Given these concerns, this analysis considers how pavement mix designs will need to evolve over the course of the 21st century.

[424] Distortion is defined as that distress in the pavement caused by densification, consolidation, swelling, heave, creep, or slipping of the surface or foundation.
[425] Rutting is defined as longitudinal depressions in the wheel paths of asphalt pavements.
[426] Asphalt Concrete is the term given pavement comprised of a mixture of asphalt , aggregate, and other admixtures as may be required.

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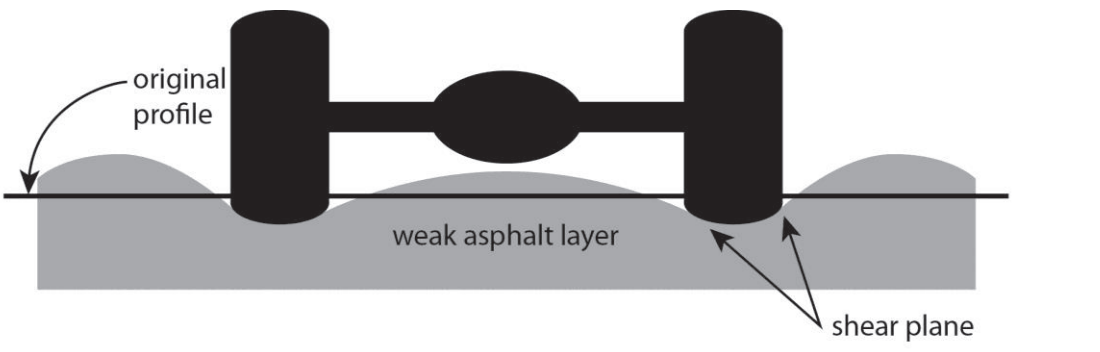
In this case study, the current practices and specifications of ALDOT were evaluated and an analysis of how climate change might affect mix designs[427] in the future was conducted. While climate change can affect pavement design in many ways,[428] the focus of this case study was limited to mix design and how that may need to change to prevent premature design failures for AC pavements from rutting and PCC pavement from cracking. It was found that no changes to mix design are required at this time in Mobile. The following sub-sections provide a brief overview of AC rutting and PCC cracking.

AC Rutting

Rutting is a distortion occurring in the wheel paths of an AC pavement (see Figure 95). It results from densification[429] and permanent deformation[430] under vehicle loads, combined with displacement of pavement materials, and affects the functional performance of a pavement. It is also a primary indicator of the structural performance of pavement. In deterioration models,[431] rutting is normally expressed as a depression depth relative to the plane of the pavement surface.

Figure 95: Diagram of Rutting in an AC Layer[432]



Rutting may be caused by several factors, including unstable AC mixes resulting from high temperatures, high asphalt content, or low binder viscosity.[433] Rutting is a common form of distress where heavy traffic loads such as heavily loaded trucks coincide with high in-service temperatures. As asphalt temperatures increase, the stiffness of the asphalt decreases, making it more prone to deformation under wheel loads.

[427] Mix design refers to the various components of a pavement. For asphalt, there are three primary components: (1) asphalt binder (a viscous petroleum-based product that essentially acts as the glue that holds the asphalt together), (2) mineral aggregate, and (3) air. Optionally, additional modifiers and additives can also be included. Of the three primary components, mineral aggregate makes up the vast majority of the mix with air and binder comprising the remainder. For concrete, the key mix components are Portland cement (acts as the binder), aggregate, water, and mineral and chemical admixtures (used to achieve higher quality concrete and / or better workability).
[428] Beyond mix design, temperature can also affect the construction and maintenance regimes for paving work. These impacts are not covered in this case study but are touched on in Section 4.4.1 . Climate change can also have an impact on pavements through changing moisture regimes. Moisture impacts on pavements and subgrades are not addressed in this case study although rapidly changing soil moisture conditions or periods of extended inundation can cause significant damage to pavements.

[429] Densification is compaction: an increase in the density of something.
[430] Permanent deformation occurs when a component does not return to its original shape after being strained.
[431] A deterioration model is a mathematical model used to predict pavement deterioration over time.
[432] Santucci, 2001
[433] Viscosity is the state of being thick, sticky, and semi-fluid in consistency, due to internal friction.

PCC Cracking

If PCC reaches too high a temperature during its placement, long-term PCC performance might be compromised. High temperatures increase the rate of hydration,[434] permeability[435] and thermal stresses,[436] and raise the chances of drying shrinkage cracking.[437] Cracking leads to decreased long-term PCC strength and durability. Most states, including Alabama, specify a maximum PCC temperature at the time of placement to mitigate the detrimental effects of hot weather. Mineral or chemical admixtures[438] can also be used in the PCC mix to help mitigate the impacts of high PCC temperatures.

It is important to understand the significance of the crack pattern in terms of the performance of PCC pavement with respect to the potential for distress development. Distress patterns can occur in one of two forms. One form is associated with wide transverse cracks that often occur with wide crack spacings or clustered crack patterns. The second form of distress is the loss of load transfer on adjacent transverse cracks leading to the development of a punchout.[439] The focus of identified failure modes of the punchout process is consequently closely aligned with the load transfer, crack width, and the effective slab bending stiffness of adjacent transverse cracks. Detailed field and laboratory study has clearly indicated that punchouts are initiated as a result of lost or reduced pavement support. Lost or reduced pavement support, though not directly related to PCC mix design, can be correlated with the formation of crack pattern development. Crack pattern development can be correlated to the temperature of the mix during placement which can be mitigated by adjustments to the mix design.

Organization of Case Study

The case study is organized around the 11 steps of the *General Process for Transportation Facility Adaptation Assessments* to illustrate how they can be applied to the topic of pavement mix design. The focus is on AC mix design but issues associated with PCC mix design are also discussed. The reason this case study focuses on AC mix design versus PCC mix design is that a majority of roadways / highways in Alabama are AC versus PCC.

Application of the General Process for Transportation Facility Adaptation Assessments

Step 1 – Describe the Site Context

There is no specific project location for this case study; instead the analysis is broadly applicable to any future highway paving project in the Mobile region where ALDOT practices for pavements would apply.

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[434] Hydration is the process whereby Portland cement (mixed with aggregates such as sand and gravel) reacts with water to produce concrete (and heat).
[435] Permeability is the state or quality of a material or membrane that causes it to allow liquids or gases to pass through it.
[436] Thermal stress is a decrease in the quality of a material that occurs due to excessive changes in temperature.
[437] Drying shrinkage cracking occurs when the concrete shrinks due to evaporation of excess water but the subgrade (materials below the concrete) and internal reinforcement restrain the concrete, causing stresses and cracking in the concrete slab.
[438] Admixtures are added to a concrete mix to improve quality and aid in the construction process.
[439] Punchouts are localized areas where the slab is cracked and broken into several pieces.

Step 2 – Describe the Proposed Facility

The proposed new facility is a generic high truck volume highway in the Mobile region, but the analysis could also be applied to low volume roads in order to achieve better pavement performance. An example of this type of facility in the Mobile region for AC pavement would be I-10 near McDuffie Terminal. An example for PCC pavement would be North Broad Street in Mobile (US 98/Alternate US90). Higher truck volume highway facilities would be more at risk for climate change impacts based on the fact that rutting is a common form of distress where heavy traffic loads (such as occur with heavily loaded trucks as measured by the number of Equivalent Single Axle Loads[440]) coincide with high in-service temperatures.

Step 3 – Identify Climate Stressors That May Impact Infrastructure Components

The key environmental factor to affect pavement mix design, both in terms of AC rutting and PCC cracking, is temperature. The specific temperature variables relevant to pavement mix design include the:

- Maximum seven consecutive day average high air temperature (50 % reliability[441])
- Absolute minimum low air temperature on the coldest day (50 % reliability)

For AC mix design, the main materials in consideration are asphalt, binders and aggregates: the temperature variables listed above are used to assist in the selection of these materials. ALDOT uses a Superpave[442] system to help with the selection process.

For binders, the concept of Performance Grading (PG) is based on the idea that a hot mix AC binder's properties should be related to the conditions under which it is used. For AC binders, this involves expected climatic conditions as well as aging considerations. The PG system uses a common battery of tests and specifies that a particular AC binder must pass these tests at specific temperatures that are dependent upon the climatic conditions in the area of use. A binder used in the Sonoran Desert of California and Arizona, for instance, would have different properties than one used in the Alaskan tundra.

A suitable PG AC binder will minimize thermal cracking under cold temperatures (due to shrinkage of the material) while simultaneously minimizing traffic-induced rutting under hot temperatures. Pavement designs have multiple AC layers usually of varying asphalt grades. There is usually a surface, intermediate, and base course layer. Each layer would need to be reviewed for appropriate PG grade adjustment due to temperature within a given region: this assessment considers only the surface layer.

[440] ESAL is the loading equivalent of one, 18,000 pound (80 kilonewton) axle.
[441] Reliability refers to the probability that the given temperature value will be exceeded in any particular year.
[442] The U.S. Strategic Highway Research Program developed the Superpave system to specify optimal hot asphalt pavement mixes for given temperature and traffic conditions based on empirical research.

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Grades are assigned in 10.8°F (6°C) increments for both minimum and maximum pavement temperatures as illustrated in Table 53. The naming of each binder specification corresponds with the metric pavement temperature ranges for which it is rated. For example, a PG 58-22 AC binder meets a seven-day maximum pavement temperature of 58°C (136.4ºF) and a minimum pavement temperature requirement of -22°C (-7.6°F). The maximum PG threshold refers to a temperature within the pavement, normally about 0.8 inches (20 millimeters) from the surface, while the minimum PG threshold refers to the actual surface pavement temperature. In practice, maximum temperature PG thresholds are adjusted upward one or more 10.8°F (6°C) increments to account for traffic and load considerations. Note that binder specifications are defined in terms of *pavement* temperature, not ambient temperature.

The conversion of ambient temperature to maximum pavement temperatures for use in selecting PG grade asphalts can be accomplished using the following formula: [443]

$$T_{20mm} = (T_{Air} - [0.00618][lat]^2 + [0.2289][lat] + 42.2°C)(0.9545) - 17.78°C$$

Where,
T_{20mm} = High pavement design temperature 0.8 inches (20 millimeters) below the surface
T_{Air} = Maximum seven consecutive day average high air temperature (°C)
lat = Geographical latitude of the site in degrees

Likewise, the conversion of ambient temperatures to minimum pavement temperatures can be done through the following formula:

$$T_{Min} = (0.859)(T_{Air}) + 1.7°C$$

Where,
T_{Min} = Minimum pavement design temperature
T_{Air} = Absolute minimum low air temperature on the coldest day

[443] Fwa, 2005 (pg. 7-27)

Table 53: Performance Grade AC Binder Specifications by Temperature[444]

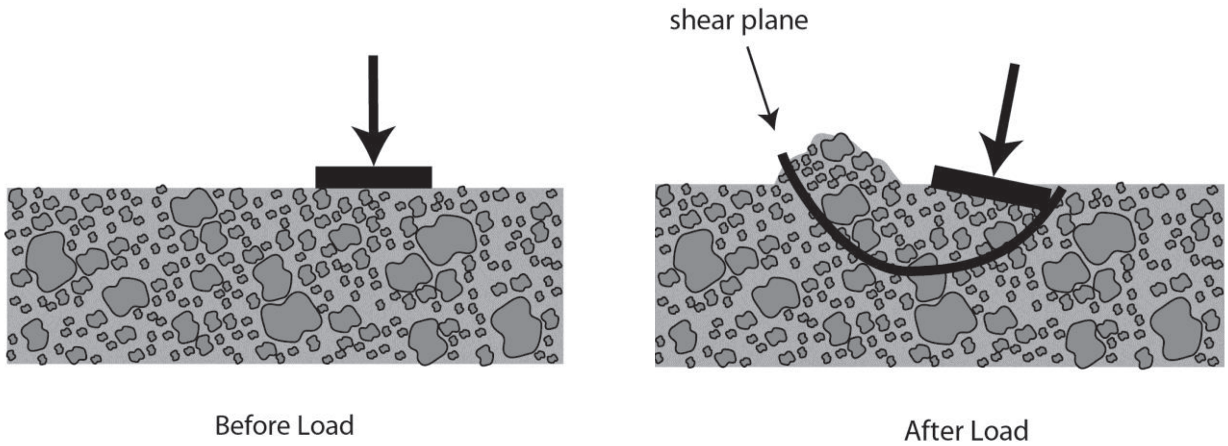
Extreme Minimum Pavement Temperature (°C)	Seven-Day Maximum Pavement Temperature (°C)					
	46 (114.8°F)	52 (125.6°F)	58 (136.4°F)	64 (147.2°F)	70 (158°F)	76 (168.8°F)
-40 (-40°F)	PG 46-40	PG 52-40	PG 58-40	PG 64-40	PG 70-40	PG 76-40
-34 (-29.2°F)	PG 46-34	PG 52-34	PG 58-34	PG 64-34	PG 70-34	PG 76-34
-28 (-18.4°F)	PG 46-28	PG 52-28	PG 58-28	PG 60-28	PG 70-28	PG 76-28
-22 (-7.6°F)	PG 46-22	PG 52-22	PG 58-22	PG 64-22	PG 70-22	PG 76-22
-16 (3.2°F)	PG 46-16	PG 52-16	PG 58-16	PG 64-16	PG 70-16	PG 76-16
-10 (14°F)	PG 46-10	PG 52-10	PG 58-10	PG 64-10	PG 70-10	PG 76-10

Another factor in mix design that affects rutting is the type of aggregate used. Aggregates refer to any granular material formed from a natural rock substance. These are materials extracted directly from the ground in quarries or pits. They can be either sand and gravel or hard rock. Aggregate properties and aggregate gradation[445] play major roles in the potential for rutting of an AC pavement. The rutting resistance of an AC mix depends on the shear resistance[446] of that mix.

Figure 96 illustrates the shear loading behavior of aggregate. If the shear stress created by repeated wheel load applications exceeds the shear strength of the mix, then permanent deformation or rutting will occur. Cubical, rough-textured aggregates are more resistant to the shearing action of traffic than rounded, smooth-textured aggregates. Cubical aggregates also tend to interlock better, resulting in a more shear resistant mass of material. In addition, increased compaction during construction or the use of higher percentages of coarse aggregate[447] fractions in the aggregate gradation provides more stone-to-stone contact in the AC mix which, in turn, helps reduce pavement rutting. Thus, as temperatures and / or vehicle loads rise, the specification of the aggregate mix should include more cubical and rough-textured materials.

[444] FHWA, 2002b
[445] Aggregate gradation is the distribution of aggregate particles among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sizes (sieve openings) or the percentages between certain ranges of sizes (sieve openings).
[446] Shear resistance is measured as the force required to pull the pressure-sensitive material parallel to the surface to which it was affixed, under specific conditions.
[447] Coarse aggregate is naturally occurring, processed or manufactured, inorganic particles in prescribed gradation or size range, the smallest size of which will be retained on the number four (0.2 inch [4.8 millimeter]) sieve.

Figure 96: Illustration of Aggregate Shear Behavior[448]



Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes

The climate scenarios used for this case study were developed in Task 2 of the broader Gulf Coast Study Phase 2. Two specific temperature scenarios were developed for the 21st century; a "Warmer" narrative and a "Hotter" narrative. The "Warmer" narrative represents the 5th percentile (mean-1.6 SD[449]) of all the climate model outputs under the range of climate scenarios considered, whereas the "Hotter" narrative represents the 95th percentile outputs (mean+1.6 SD). Please refer to the *Climate Variability and Change in Mobile, Alabama*[450] and *Screening for Vulnerability* [451]for more details on how these narratives were developed.

Table 54 below provides a summary of projected changes to the pavement design-related temperature variables discussed in Step 3 under both the "Warmer" and "Hotter" narrative. The "Warmer" narrative projects a slight decrease in temperature of the coldest day in the near term and a slight increase in the maximum seven consecutive day average high temperature. On the other hand, the "Hotter" narrative projects a large increase in the temperature of the coldest day and the seven consecutive day average high temperature over the course of the 21st century.

Step 5 – Assess Performance of the Proposed Facility

ALDOT currently recommends the use of either PG 67-22 or PG 76-22 in the Mobile region, depending on expected traffic loads.[452] PG 67-22 is the most common application; PG 76-22 is specified for use only as a surface layer on high traffic load roads. To evaluate whether these binder specifications will need to change in the future due to climate change, the temperature

[448] Santucci, 2001
[449] Standard deviation
[450] USDOT, 2012
[451] USDOT, 2014
[452] ALDOT, 2012

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projections in Table 54 were converted to pavement temperature values to enable selection of the appropriate PG rating from Table 53 using the formula shown in Step 3.

Table 54: Observed and Projected Pavement Design Related Temperature Variables in Mobile, Alabama[453]

	Observed (Model Baseline)[454] 1980-2009	"Warmer" Narrative			"Hotter" Narrative		
		2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
Maximum Seven Consecutive Day Average High Temperature (°F) (50th Percentile)	94 (34.4°C)	94 (34.4°C)	95 (35°C)	96 (35.6°C)	97 (36.1°C)	99 (37.2°C)	103 (39.4°C)
Coldest day (°F) (50th Percentile)	20 (-6.7°C)	19 (-7.2°C)	20 (-6.7°C)	20 (-6.7°C)	23 (-5°C)	25 (-3.9°C)	28 (-2.2°C)

The analysis first verified that the PG 67-22 and PG 76-22 specifications are appropriate for Mobile's current climate. This was found to be the case. With regard to future climate, the analysis determined that no changes would be required to the minimum temperature rating (-22) under either climate narrative since, at most, the 50th percentile coldest day is expected to only get one degree Fahrenheit cooler than present. This translates to a minimum pavement temperature of 23.9°F (-4.5°C), well within the tolerance of the -22 specification. In terms of the maximum temperature rating with the lowest threshold (67), the analysis found that no change to this rating would be required under either of the narratives at any of the three future time periods tested. The highest projected ambient temperature across any of the scenarios evaluated, 103°F (39.4°C) under the "Hotter" narrative in the 2070-2099 time period, produces a maximum pavement temperature of 152.3°F (66.8°C), within the range of the 67 (and 76) maximum temperature ratings. Thus, the PG 67-22 and PG 76-22 specifications for AC binder are determined to be adequate for future projects in Mobile throughout the 21st century, despite the likely rise in projected temperatures. That said, the PG 67-22 specification comes close to being inadequate late this century if the "Hotter" narrative is realized.

Step 6 – Identify Adaptation Option(s)

As noted in Step 5, the current PG 67-22 and PG 76-22 specifications are expected to continue to be appropriate throughout the 21st century in Mobile. Thus, no adaptations to current AC mix design specifications are anticipated to be required in Mobile at this time. In other locations where projected temperature changes are greater, changes to binder specifications may need to be made and the appropriate adaptation in the mix can be determined by consulting Table 53.

[453] Source: USDOT, 2014. Note: Figures shown represent an average across the five regional weather stations.
[454] The observed values represent calibrated statistical values derived from climate models as opposed to actual historical observations. Use of the model baseline allows for a more consistent comparison of past and projected future climate conditions.

In addition, as previously mentioned, aggregate type also plays a role in preventing rutting. Thus, an additional adaptation measure for locations expecting much warmer conditions would be to adjust the aggregate specifications of the mix. Specific options for doing this could include the following:

- Moving to a coarser aggregate that increases compaction during construction
- Using higher percentages of coarse aggregate fractions in the aggregate gradation thereby providing more stone-to-stone contact in the AC mix which, in turn, helps reduce pavement rutting
- Using Stone Matrix Asphalt (SMA) mixes. These mixes are designed to provide more direct stone-to-stone contact to help resist rutting. In an SMA mix, the stone skeleton is intended to carry the load and the fine aggregate particles are used to fill up the void space in the skeleton. In a dense graded mix, the fine aggregate is locked between larger aggregate particles and the load is transferred through the entire uniformly graded structure.

Other adaptation considerations, outside of mix design changes, that could be utilized to help minimize rutting in areas with projected hotter temperatures due to climate change could include:

- Use of thicker pavement sections at the time of initial design
- Consideration of PCC pavement versus AC pavement in certain applications
- Changing the frequency of maintenance

As with any complete pavement design process, these options should be subjected to a life-cycle cost comparison.

PCC

Modern specifications should account for the use of improved materials in order to ensure improved PCC performance under hotter placement conditions; conditions likely become more common in Mobile and throughout much of the country with climate change. To provide improved performance for sections paved under hot weather conditions, one adaptive option is that Continuously Reinforced Concrete Pavement (CRCP)[455] reinforcement standards be re-designed to provide steel quantities for specific use during hot weather conditions, and that an end result specification that limits the maximum in place PCC temperature during hydration be implemented[456]. The higher expense of this option especially warrants a life-cycle cost analysis. Hydration relates to the fact that when Portland cement[457] is mixed with water, heat is released. This heat is called the heat of hydration, the result of the chemical reaction between cement and water. The heat generated by the cement's hydration raises the temperature of PCC.

[455] Continuously reinforced concrete pavement is Portland cement concrete pavement with continuous longitudinal steel reinforcement and no intermediate transverse expansion or contraction joints.
[456] FHWA has developed concrete pavement design software, HIPERPAV III® that includes modules to address increased temperature and hydration procedures
[457] Portland cement is a product manufactured from limestone and clay that hardens under water and acts as the binder in a concrete mix.

One possible measure to minimize the potential problems associated with hot weather concreting can be to control the PCC mixture temperature. Under hot weather placement conditions, an effort should be made to keep the PCC temperature as low as economically feasible. By controlling the temperature of the ingredients, the temperature of the fresh PCC can be regulated.

Other possible measures could include (in the order of likely feasibility):

- The scheduling of placement activities during the times of the day or night when the weather conditions are favorable
- Minimizing the time to transport, place, consolidate, and finish the PCC
- The use of PCC materials and proportions with satisfactory performance in place under hot weather conditions
- The use of a PCC consistency that allows rapid placement and effective consolidation at high temperatures.
- Protecting the PCC from moisture loss at all times during placement and during its curing period such as by covering PCC with impervious paper or plastic sheets or applying membrane-forming curing compounds
- Use of cooled PCC, which can be achieved by using chilled mixing water, ice in the mixture, or rarely, the use of liquid nitrogen to cool the mixing water or the PCC mixture, or the cooling of the coarse aggregate

Step 7 – Assess Performance of the Adaptation Option(s)

As no adaptation option was required with respect to AC mix design, the performance of the adaptive design options was not formally assessed for this case study. If different climate scenarios for a given area required different binder specifications, this part of the analysis should entail a comparison documenting how the specification optimized for each scenario performs under all the other scenarios tested.

Step 8 – Conduct an Economic Analysis

An economic analysis of each adaptation option was not conducted for this case study; however, it is recommended that an analysis that includes a life-cycle cost comparison be conducted prior to determining whether and how to change pavement design standards if temperatures show signs of changing over time. Generally speaking, adjusting PG grades of mix designs based on temperature changes is a fairly low cost adjustment and a good choice economically over the long term relative to the chance of premature rutting in new AC pavement which could require costly maintenance and repairs.

Step 9 – Evaluate Additional Decision-Making Considerations

If an adaptation was required, before selecting an option one would need to consider whether there are any other specific factors relevant to their operations and include those into their decision-making. For pavement mix design, these factors might include:

- Broader project sustainability beyond just climate change adaptation (e.g., the relative sustainability factors of AC versus PCC in the project area)
- Maintenance funds availability
- Capital funds availability
- Stakeholders' expected quality or level of service

Step 10 – Select a Course of Action

Since climate projections do not show a change in temperature patterns great enough to require changes to pavement mix design in Mobile, the recommended course of action for new projects occurring at this time is not to undertake any adaptations to current practice. That said, if evidence emerges that temperatures are trending in line with the "Hotter" narrative, then starting mid-century it may make sense to re-evaluate changing the PG 67-22 standard to a higher specification that can handle heat better. The cost of the potential adaptations / changes should be weighed against potential benefits (avoided traffic delays and construction costs associated with repairing pavements if they fail early), and with an understanding of the leanness of budgets now and in the future. For PCC pavements, since the analysis is about practices on the day of installation, it probably doesn't make sense to change construction techniques until temperatures are too hot to support current practices.

Step 11 – Plan and Conduct Ongoing Activities

Agencies need to monitor temperature changes to assess whether conditions are trending in line with the climate scenarios tested. Once an upward trend of higher seven consecutive day temperatures is clearly established, the mix design could be adjusted to account for these changes. Current pavement design procedures and software include consideration of environmental factors. Agencies' pavement engineers can incorporate forecasted changes in the environmental factors into the pavement design process. As noted above, such proactive adaptations might start first on the most critical infrastructure, perhaps even prior to a PG specification threshold being crossed, and then proceed to less critical infrastructure once it's clear a new climate regime has arrived. It is important as well to monitor all new pavements to ascertain if the current and, in the future, revised mix designs or other measures incorporated into the new pavement design perform as expected.

Conclusions

This case study provided a high-level, non-site specific analysis of how projected changes in temperature in Mobile, Alabama might impact pavement mix design on AC and PCC roads. It was determined that under both the "Warmer" and "Hotter" narratives, temperature changes were not great enough to require any adaptations from current practice at this time although this conclusion may need to be re-evaluated later in the 21st century. The primary lesson learned from this case study is the need to monitor temperature changes, periodically update historical

temperature records, and use climate projections where appropriate instead of simply using outdated 20th century numbers.

Moving from exploratory research that raises awareness of climate change to practical guidance aimed at reducing costs and safeguarding infrastructure will require additional efforts and collaboration. Pavement engineers, with assistance from government agencies and climate change experts, should be encouraged to develop a protocol or guide for considering potential climate change in the development and evaluation of future designs. The guide should extend beyond the narrow focus on pavement mix design in this case study to incorporate all elements of climate change impacts on pavement design (e.g., subbase, drainage, pavement texture). Researchers should explore if and how the AASHTOWare Pavement Mechanist Empirical (ME) Design software[458] can be adapted to incorporate climate change. The current software allows input of historic weather station data for climate models for a given project location. It then takes this data and projects weather conditions for the design life of the pavement. Amending the software to incorporate climate change projections would be a logical next step in its development.

[458] AASHTO, 2014

4.4.10 Continuous Welded Rail Exposure to Temperature Changes

Introduction

Temperature is a critical consideration in both the laying of rail tracks and in their continued reliable condition. If rail temperature is not properly considered in the laying of track, the track structure can become disturbed in periods of extreme heat or cold requiring maintenance expenditures, causing train delays, and leading to a heightened risk of derailments. The physics are rather simple. Steel rail will expand with heat, possibly resulting in a track perturbation commonly called a sun kink (see Figure 97). In extreme cold weather, the contracting rail can literally pull itself apart, more commonly, at the joints or the welds.

Case Study Highlights

Purpose: To understand whether continuous welded rail (CWR) in Mobile could be vulnerable to projected increases in temperature.

Approach: Considering a generic CWR in Mobile, the minimum desired rail neutral temperature was calculated using an equation from AREMA (2013). Then, an evaluation was made as to whether the neutral temperature would need to change under the projected future temperatures.

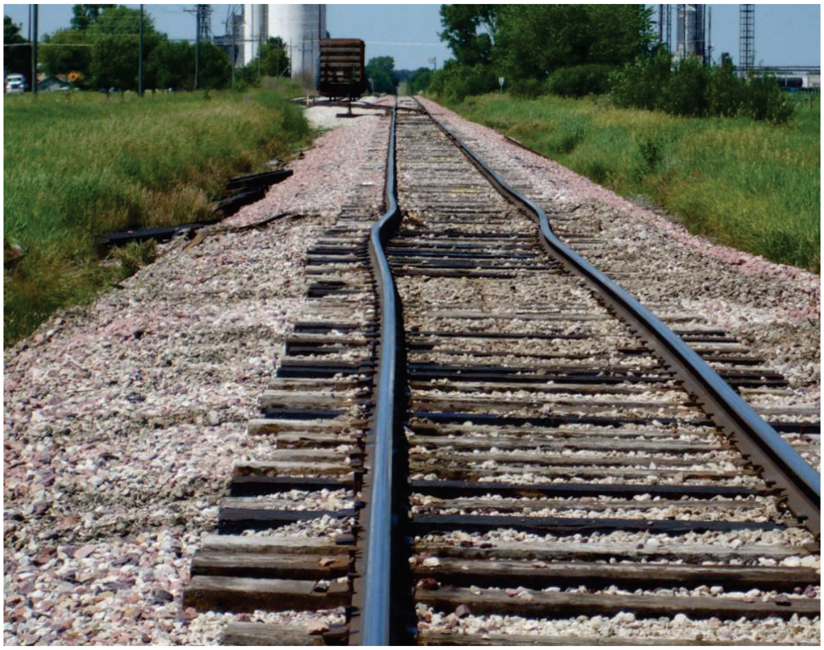
Findings: The rail in Mobile may not be vulnerable under less severe climate change conditions, but could be vulnerable under more severe ones.

Viable Adaptation Options:

- Increase rail neutral temperature
- Ensure that ballasted tracks have sufficiently wide shoulders to support the ties

Other Conclusions: Monitoring temperature trends, and keeping track of buckling or kinking incidents, may help alert track managers to the appropriate time to take proactive adaptation measures.

Figure 97: Example of a Hot Weather Sun Kink[459]



According to the Federal Railroad Administration (FRA) Office of Safety database, there were over 150 derailments nationwide between 2005 and 2009 related to track buckles or sun kinks, resulting in $43 million in damages.[460] Railroads work very hard to avoid and prevent derailments because of their cost, the resulting damages and claims, and the potential for personal injuries and fatalities. With ambient temperatures greater than 95^0 F (35°C) railroads issue slow orders whereby train speeds are lowered. This has the effect of decreasing stress on the rail and allows train crews a few more seconds to identify any track perturbations. As a practical matter, the speed restrictions bring passenger train speeds down to freight speeds. On a freight only line, the effect on operations is minimal until a track perturbation actually occurs or is discovered.

Cold weather pull-aparts create operational challenges but, likely, fewer derailments because if a pull-apart occurs along the track, the integrity of the track signal circuit[461] may be breached and the wayside signals would display a “stop,” “stop and proceed,” or “proceed at restricted speed” indication (more often than expected the pull-aparts do not drop the signal. This is caused by track components, like tie plates, bridging the connections). A train normally can negotiate a pull-apart rail gap of three inches (7.6 centimeters) or less at slow speed (10 miles per hour [16.1 kilometers per hour] or less). Where the broken rail gap does not exceed three inches (7.6

[459] Iowa DOT, 2013
[460] Zhang and Nizer, 2010
[461] A track signal circuit refers to the electrical current run through rails that is used to detect train locations and aid in train signaling.

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centimeters), the train can be "walked" across the gap under the supervision of a qualified maintenance of way supervisor. Otherwise, the broken rails would need to be de-stressed and reconnected by means of a temporary joint bar until the rails can be re-welded.

Recognizing the operations and safety challenges temperatures can pose to rails, this section will investigate the impacts that projected temperature changes might have on new track laying and maintenance of way practices in the Mobile region over the 21st century using the *General Process for Transportation Facility Adaptation Assessments*. The focus will be on Continuously Welded Rail (CWR)[462] which is most prevalent on mainline Class 3 tracks[463] in the Mobile area and where the biggest impacts would be felt from delays and derailments owing to temperature-related problems. Light rail and subway rail lines, although also sensitive to temperature, have different characteristics from the rails studied here and are not included in this analysis. The assessment finds that track-laying practices may need to be adapted in the future under one of the climate scenarios tested. However, no adaptation actions are recommended at this time except to monitor conditions as adaptations can readily be made to the existing track if conditions warrant.

Application of the General Process for Transportation Facility Adaptation Assessments

Step 1 – Describe the Site Context

Three Class I[464] railroads own and maintain rail lines in the Mobile region; CSX, Norfolk Southern, and Canadian National. Although subject to the same regional environmental factors, each railroad has its own approach and practices for laying and maintaining rails. This case study is intended to apply to all of the railroads, although much of the analysis will focus on CSX practices specifically because of data availability.

Step 2 – Describe the Proposed Facility

No specific facility is examined in this case study. Instead, the analysis is applied to a generic segment of new CWR track on one of the CSX or Norfolk Southern rail lines found to be critical in the Mobile region in the *Assessing Infrastructure for Criticality in Mobile, Alabama* report.[465]

Step 3 – Identify Climate Stressors That May Impact Infrastructure Components

The key environmental variables in the performance of rail track are the absolute expected maximum and minimum air temperatures over the lifespan of the rail installation (typically less

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[462] Rail lines consist of either CWR or jointed rail sections with CWR being most commonly employed on main line tracks and jointed rail on secondary tracks. Jointed rail was the earliest form of rail installation and consists of individual segments of rail each typically between 39 and 78 feet (11.9 and 23.8 meters) long. Jointed rails are mechanically joined by means of joint bars to firmly support the abutting rail ends and to allow longitudinal movement of the rails in the joint to accommodate expansion and contraction due to rail temperature variations. In CWR, commonly employed since the 1950s on main lines, individual rail segments are welded together into strings that can be miles long between joints allowing for a smoother ride, lower maintenance requirements, and higher speeds.
[463] FRA track classifications relate different track geometry to maximum authorized speed for freight and passenger trains. The maximum speeds for freight trains and passenger trains on Class 3 tracks are 40 and 60 miles per hour (64.4 and 96.6 kilometers per hour), respectively.
[464] Railroads are classified by the U.S. Surface Transportation Board based on their annual operating revenue over a three year period. Class I railroads are the highest revenue railroads with annual operating revenues of $250 million or more over each of the last three years (adjusted for inflation).
[465] USDOT, 2011

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than twenty years, sometimes significantly less, for mainline rail[466]). Ambient air temperatures impact rail temperatures; excessively high rail temperatures can lead to rail expansion and sun kinks and excessively low rail temperatures can lead to rail shrinkage and pull-aparts.

The concept of "neutral temperature" is of paramount importance in laying CWR in order to reduce the risk of such hazards. Neutral temperature is defined as the rail temperature in the CWR rail section that would result in zero thermal stress[467] in the rail section. Thermal stress occurs when the rail temperature increases or decreases from the neutral temperature and the rail seeks to expand or contract but is limited in its ability to do so at the ends of the string or where it is anchored. During extreme high rail temperatures, the resulting force due to rail expansion can overcome the ability of the ties and ballast shoulders to hold the rail in place leading to sun kinks. During extremely low temperatures, a rail break can occur when the resulting stress exceeds the strength of the rail section, resulting in a rail pull-apart. The resulting pull-apart gap between the broken rails is limited by the rail anchors and clips on each tie. Some railroads elect to anchor the rail at specific locations (e.g., placing an anchor at every other tie, near switches-box anchor 200 ties before and after). A more uniform distribution of the anchors may help in preventing buckling derailments.

The desired neutral temperature is determined by the temperature of the rail (not the ambient temperature) at the time of its installation and fixing to the ties.[468] There is an optimal range at which to set the neutral temperature that is based on the expected temperature patterns at the installation site: installing a rail at too high a neutral temperature might result in a higher risk of pull-aparts in cold temperatures and installing it too low may result in greater risk of sun kinks during warm temperatures.

The acceptable range for the neutral temperature is determined by the following equation:[469]

$$\text{Minimum Desired Rail Neutral Temperature} = ((2H_T+L_T)/3) + 10$$

$$\text{Maximum Desired Rail Neutral Temperature} = [((2H_T+L_T)/3) + 25] \pm 5$$

Where,

H_T = Highest rail temperature projected over its design life (in Fahrenheit)

L_T = lowest rail temperature (in Fahrenheit)

Note that the formula makes use of the highest and lowest *rail* temperatures, not the highest and lowest ambient air temperature. This is because it is the temperature of the rail, not ambient

[466] As main line rails become worn, they are typically taken up and re-used on lower speed branch lines. The ultimate lifespan of a rail can be upwards of sixty years although it might be re-laid multiple times during that period. The neutral temperature (see paragraph below this footnote) can be reset with each rail laying depending on the requirements of the new location.
[467] Thermal stress is only one of the many stresses that affect rails: other stresses come from train loads and train motions.
[468] The rail temperature at the time of installation is influenced by the ambient temperature but can be adjusted in the field as needed using specialized equipment so that the desired neutral temperature can be achieved regardless of weather conditions at the time of installation.
[469] AREMA, 2013

temperature alone, that counts when determining thermal stresses.[470] Thus, to assess the impact of changing climate conditions on the setting of neutral temperatures, it is necessary to draw a relationship between the maximum and minimum ambient air temperature (as output from climate models) and actual rail temperatures. FRA guidance states that rail temperature shall be considered 30ºF higher than ambient temperatures in hot weather and equal to ambient air temperature in cold weather.[471]

The FRA has also developed, and Amtrak has tested, a more sophisticated model for relating ambient air temperatures to rail temperatures that constitutes a rail weather system to help predict track buckling risks in real time given actual weather conditions and known track attributes.[472] Typically, the railroad knows—or can easily find out—the ambient temperature along the line. It is the *rail* temperature, however, that causes the track to expand and possibly buckle the track. This model is based on the heat transfer process of a rail exposed to the sun. A rail weather station was established and used to calibrate the model. The station was composed of a portable weather station and a short segment of rail track with sensors installed on both rails. Ambient temperatures were taken by the weather station and the rail temperature by rail thermometers. Data from these instruments were sent to a control office for further action if required. Modeled results have been compared to actual conditions; the model predicts the maximum rail temperature within a few degrees and within 30 minutes of the actual time when the high temperature occurs during the day. While it would be ideal to assess the impact of projected temperature patterns using such a system, time and budget considerations dictate that a more basic analysis using FRA's guidance relating ambient to rail temperature will be used in this case study. Exploring the possibility of using a rail weather system with projected climate inputs is, however, a recommended area for future research.

Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes

The climate scenarios used for this case study were developed under an earlier phase of the broader Gulf Coast Study. Two specific temperature scenarios were developed, a "Warmer" narrative and a "Hotter" narrative. These narratives were chosen to "bound" the range of model outputs. The "Warmer" narrative represents the 5th percentile of all the climate model outputs under the range of climate scenarios considered, whereas the "Hotter" narrative represents the 95th percentile outputs. Please refer to the *Climate Variability and Change in Mobile, Alabama*[473] and the *Screening for Vulnerability* report[474] for more details on how these scenarios were developed.

As shown in Table 55, each scenario entails different temperature patterns. Under the "Warmer" narrative, maximum temperatures are projected to remain largely unchanged while minimum

[470] Due to solar radiation, the rail will be much hotter than the ambient air temperature during the day.
[471] FRA, 2013
[472] Zhang and Nizer, 2010
[473] USDOT, 2012
[474] Source: USDOT, 2014. Note: Figures shown represent an average across the five regional weather stations.

temperatures are projected to decrease slightly. With the "Hotter" narrative, both maximum and minimum temperatures are projected to increase.

Table 55: Projected Changes to Maximum and Minimum Temperatures in Mobile, Alabama[475]

	Observed (Model Baseline)[476] 1980-2009	"Warmer" Narrative			"Hotter" Narrative		
		2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
Maximum Annual Highest Maximum Temperature (°F)	103	102	103	103	106	109	113
1st Percentile Coldest Day (°F)	4	-1	0	1	15	18	20

Step 5 – Assess Performance of the Proposed Facility

As discussed in Steps 1 and 2, the proposed facility is a new CWR installation anywhere within the Mobile region (either on a new rail line or a rail replacement on an existing line). Per the guidance for new facilities in the *General Process for Transportation Facility Adaptation Assessments*, the base case proposed facility should be based on a traditional design or practice that one would employ without consideration of climate change. Thus, in this case study, the base case is defined as the standard practice, the standard neutral temperature, one would employ when laying rail in the Mobile region today.

Although constrained by the formula discussed above, each railroad operating in the Mobile region employs its own practices when defining what specific neutral temperature will be used in each installation. FRA requires each railroad to develop its own plan, which then becomes a self-regulating proscriptive document. This analysis will focus on one of Mobile's Class I railroads which currently uses 100ºF (37.8°C) as the neutral temperature on all their CWR tracks in the Mobile region. Using the neutral temperature formula shown in Step 3 and the FRA guidance which states that rail temperatures can be assumed to be 30°F (16.7°C) higher than the ambient temperature in hot weather, it was determined that the acceptable neutral temperature range given historical conditions is between 100ºF (37.8°C) and 115ºF +/- 5ºF (46.1°C +/- 2.8°C).

Referring to the formula in Step 3, an example of the calculation for the minimum desired rail neutral temperature under existing conditions is as follows:

Observed Maximum + FRA Guidance = H_T

[475] USDOT, 2014
[476] The observed values represent calibrated statistical values derived from climate models as opposed to actual historical observations. Use of the model baseline allows for a more consistent comparison of past and projected future climate conditions.

$103 + 30 = 133 = H_T$

$((2H_T + L_T) / 3) + 10$ = Minimum Desired Rail Neutral Temperature

$(2\text{x}133 + 4) / 3 + 10$ = Minimum Desired Rail Neutral Temperature

100°F (37.8°C) = Minimum Desired Rail Neutral Temperature

Thus, the sample railroad's neutral temperature of 100ºF (37.8°C) is representative of the lower end of the acceptable range.

Next, an evaluation was made to determine if the neutral temperature of this railroad would need to change under the "Warmer" and "Hotter" Climate narratives. Table 56 shows the acceptable "Warmer" and "Hotter" narrative neutral temperature ranges for various future time periods. As shown in the table, the current example railroad's practice of setting a neutral temperature of 100ºF (37.8°C) would remain acceptable throughout the 21st century under the "Warmer" narrative. However, a 100ºF (37.8°C) neutral temperature would be inadvisable under the "Hotter" narrative at all future time periods; continuing to use this neutral temperature might increase the risk of sun kinks in the future.

Table 56: Acceptable Rail Neutral Temperature Ranges (ºF) in Mobile Considering Climate Projections

	Current Range	Projected 2010-2039	Projected 2040-2069	Projected 2070-2099
"Warmer" Narrative	110-115+/-5	98 to 113+/-5	99 to 114+/-5	99 to 114+/-5
"Hotter" Narrative		106 to 121+/-5	109 to 124+/-5	112 to 127+/-5

Step 6 – Identify Adaptation Option(s)

As noted above, no adaptive actions to this railroad's neutral temperature practices would be required under the "Warmer" narrative. The "Hotter" narrative, on the other hand, would require adaptive actions because the current neutral temperature used by this railroad would fall below the acceptable range given projected temperature increases. It should be noted that neutral temperature does not stay at the set values. Based on location, grade, traffic, and maintenance activities the neutral temperature will shift or drift typically in down direction. Some railroads bias to the highest neutral temperature in the acceptable range so when this drift occurs, it will stay in the acceptable range longer.

The primary adaptation action that could be taken on new CWR track would be to increase the rail neutral temperature to within the ranges shown in the bottom row of Table 56 when laying new track. If necessary, rail neutral temperature can be reset on existing track by removing, re-stressing, and reinstalling the rail. Activities such as this are frequently bundled into a comprehensive track maintenance program, rather than it being a program in itself. An additional adaptive action, and one that could be implemented on existing rail lines as well, would be to

ensure that ballasted tracks are constructed and maintained with minimum one foot (0.3 meter) wide shoulders to provide lateral support to the ties. Frequently, the buckled track results from insufficient ballast section. A fully ballasted track section with maintained shoulders provides the resistance to tie displacement caused by lateral rail forces during extreme high rail temperatures. Ensuring ballast is fully deployed and properly maintained can help lessen the risk of track buckling incidents.

Step 7 – Assess Performance of the Adaptation Option(s)

The likelihood of either the "Warmer" or the "Hotter" narrative occurring cannot be determined due to uncertainties in climate modeling. Thus, it is prudent to consider how each of the two adaptation options for the "Hotter" narrative discussed in Step 6 would perform if they are implemented but there are no climate changes or if the "Warmer" narrative were to occur. With respect to increasing the neutral temperature in line with the ranges shown in the bottom row of Table 56, this adaptation option would perform acceptably under the "Warmer" narrative so long as the increase in the neutral temperature is kept below 115ºF (46.1 ºC). The second adaptation option, monitoring to insure that the ballasted track section with shoulders is maintained, would be beneficial under every climate scenario.

Step 8 – Conduct an Economic Analysis

An economic analysis was not included in this case study and is not recommended in the case of rail neutral temperature issues. Rail neutral temperature is very costly to measure on in-service tracks using current techniques. New less expensive methods are being developed and should be available in the near future. There is little to no added cost to setting different rail neutral temperatures and the maintenance of a fully ballasted track should already be a part of the railroads maintenance program.

Step 9 – Evaluate Additional Decision-Making Considerations

Each railroad will need to consider whether there are any specific "soft" non-economic factors relevant to their operations and factor that into their decision-making. Two such considerations might be safety and public relations issues related to derailments caused by sun kinks or pull-aparts. What is the risk tolerance of the railroad to such concerns? Note that, to some extent, this might tie back to the materials typically hauled on that rail segment (e.g., rail lines commonly used to haul hazardous materials may be more a priority for re-setting neutral temperatures than those that primarily handle coal and grain).

Step 10 – Select a Course of Action

The purpose of this engineering case study was to determine if new rails on a Mobile area railroad were vulnerable enough to projected temperature changes to consider some sort of adaptation in track laying procedures. The investigation showed that standard practices in place within Mobile today are acceptable if the "Warmer" narrative bears out and unacceptable if the "Hotter" narrative were to occur. However, there is uncertainty as to which scenario will actually

happen. The prudent course of action is therefore to continue to monitor temperature trends and incident levels to see if they are trending along the lines of the "Hotter" narrative and, if so, at some point in the future consider changing rail neutral temperature practices. For existing rail lines, this may necessitate relaying the track and / or beefing up ballast shoulder maintenance.

Step 11 – Plan and Conduct Ongoing Activities

In general, sound maintenance and good inspections will continue to be the keys to future derailment prevention. When accidents do occur, railroads should continue to track the number of heat and cold-related incidents on their facilities and adjust practices accordingly based on climate changes. FRA's R&D department is working on low solar absorption coatings for rail that will significantly reduce the heat absorbed by the rail and reduce overall peak rail temperature. These coatings could significantly reduce the risk of track buckling. Agencies with responsibility for rail facilities should stay apprised of the results of this research.

Conclusions

This case study determined that projected climate changes will have an impact on the laying of CWR rail tracks in Mobile if the "Hotter" narrative is realized. The rail neutral temperature will need to be raised under this climate scenario. The "Warmer" narrative will not require a change in current rail laying practices in Mobile.

A similar evaluation of rail neutral temperature practices should be considered more broadly for other portions of the country. The viability of using FRA's rail weather system for this analysis should also receive consideration as a future research project.

4.4.11 Operations and Maintenance Activity Exposure to Climate Change and Extreme Weather Events

Introduction

Case Study Highlights

Purpose: Discuss how operations and maintenance (O&M) are affected by climate stressors.

Approach: An asset-specific engineering assessment was not conducted for this case study, since it was focused on O&M and not actual infrastructure design. Using Mobile as an example, this case study discusses how O&M can be disrupted generally, and how transportation organizations can adapt and prepare for these challenges.

Findings: Climate impacts on O&M activities can cause strains on budget and service disruptions.

Adaptation Measures: Careful planning and training can help minimize impacts on O&M. Mobile-specific examples are provided throughout this case study.

Operating and maintaining transportation facilities and networks is critically important to the performance and longevity of transportation systems. Operations and maintenance (O&M) activities must address significant ongoing challenges such as aging infrastructure and increases in traffic volumes as well as the added threat of long-term climate change impacts. Operations discussed in this section primarily pertain to the management of traffic flow despite disruptions – in this case, as a result of climate change or extreme weather events. Examples of operations activities under this context include emergency response protocols, pre-deployment of emergency supplies and equipment, use of Intelligent Transportation Systems (ITS) to disseminate critical information to travelers, or established procedures for emergency closures of roads or bridges. Maintenance, on the other hand, refers to the process of maintaining or preserving transportation assets (e.g., bridges, pavement, embankments, signage). In this section, maintenance activities are characterized as either "planned" (including "preventive" and "routine" maintenance) or "on-demand" (also known as "reactive" or "corrective" maintenance).

This section discusses how weather and climate may influence O&M activities and how current activities may be adapted to reduce the vulnerability of transportation systems to weather and climate-related risks. While this chapter primarily focuses on maintenance, discussion of operations, such as emergency management and ITS strategies from interviews in the Mobile Area are included as relevant to maintenance practitioners. Highways receive primary attention but examples from other modes are provided as well, where applicable. The section first provides an overview of how O&M activities are organized, planned, and performed on the highway system. Second, it discusses how these activities could be affected by climate change due to impacts to the maintenance crews. Finally, it recommends improvements to O&M procedures in the face of changing environmental conditions, in general, and specific changes in practice identified during the Gulf Coast Project.

An Overview of Transportation O&M

Daily O&M activities influence how users experience the transportation system more than any other function of transportation agencies.

Operations

Operations encompass management of the flow of traffic and coordinating responses to crashes and disruptions due to weather and other factors. Operations range from minute-to-minute reporting of and response to traffic conditions through active traffic management (e.g., traffic lights) and the fine tuning of the Intelligent Transportation System (ITS) components (e.g., Variable Message Signs (VMS), ramp meters, roadway and weather sensors) to the coordination of major responses to natural or manmade disruptions. Operations for a transportation system (particularly for a highway system) tend to be more centralized than maintenance due to the level of coordination needed to oversee traffic flow over larger geographic regions.

Efficient and effective system operations are an important component of overall transportation system performance. One estimate indicates that traffic incidents account for 25 percent of the nation's traffic congestion, with poor traffic signalization accounting for another five percent, and bad weather accounting for yet another 15 percent.[477] The exact percentages will vary based on location. As the severity of an incident increases, more agencies become involved with a corresponding need for coordination across state DOTs, emergency management agencies, emergency responders, enforcement agencies, public health officials, and humanitarian relief organizations.[478] This need for a coordinated response was demonstrated following recent weather-related natural disasters such as Hurricanes Katrina and Sandy and Tropical Storm Irene, tornadoes in Oklahoma, and landslides in Washington.

Maintenance

Maintenance activities are conducted by dedicated local maintenance crews. The activities they perform fall within two key categories:

- Planned activities (includes “preventive” and “routine”) tend to involve activities that can be scheduled with some amount of certainty, such as routine maintenance paving or grass mowing.
- On-demand (also known as “reactive” or “corrective”) activities involve issues that occur on an unscheduled basis, such as damage to a sign or the appearance of a pothole.

Maintenance activities are generally undertaken by agencies responsible for a particular jurisdiction, such as the state highways within a particular county or a collection of counties, typically referred to as a “division” or “district.” or “residency”). While cooperation with adjacent districts is by no means atypical, their activities tend to be specific to a fixed geography.

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[477] FHWA, 2005
[478] Lockwood, 2008; AASHTO, 2013

Each district is typically equipped with the materials, machinery, and training needed to conduct a wide range of these activities on both a planned and on-demand basis.

Overview of the O&M Planning and Budgeting Process

Unlike a capital project that is part of a larger investment program, O&M activities are line items in an agency's budget and stand alone in terms of program accountability. The budget is tied to current and projected revenue and is fixed (no borrowing). Allocations are typically broken down by major program areas (e.g., pavements, bridges, signs, drainage, signal maintenance, emergency response, and contingencies) and activities are planned and implemented throughout the year with adjustments as needed within total funding availability. O&M expenditures are generally considered non-capital (i.e., "cash" expenditures), and are typically strained due to the general shortage of public agency "cash."

The fixed nature of O&M budgets has implications for planned versus on-demand expenses. On-demand activities may increase as the system ages, traffic levels increase, and increased urbanization causes greater runoff. As changes in climate add additional stress onto the system, on-demand activities will require even more resources. Due to the fixed nature of O&M budgets coupled with the dynamic maintenance needs in response to on-the-ground changes in condition, when funds are directed to on-demand activities, resources for planned activities become increasingly constrained, and the overall resource needs increase. Because many of the "planned activities" include preventive and routine maintenance designed to keep the system in a state-of-good-repair, shifting resources away from these activities may undermine the lifecycle management of the asset(s), leaving the system *more* vulnerable to extreme weather events over the long term. Through improved transportation asset management, however, a whole-life view of all assets can be provided to allow monitoring, tracking, and analysis of how funding strategies affect asset condition, and can allow an agency to make policy and strategic decisions regarding funding (such as cross-asset decision making or investment decisions).

Weather and Climate Impacts on O&M

Virtually all of the activities performed by maintenance crews are weather-dependent to a degree. In some cases, the work cannot be completed due to the weather events effect on the O&M activity (e.g., painting in the rain) and at other times it cannot be completed due to worker safety concerns (e.g., extreme heat days). Table 57 illustrates highway maintenance that cannot be completed during certain weather events. Heavy precipitation, lightning, and strong wind affect almost all maintenance activities. Severe storms will also disrupt most activities as listed in Table 57 and even a light rain or moderate wind can be enough to delay activities like painting or sign replacement. Increased temperatures are more likely to affect the maintenance crews' ability to work rather than affecting the work product.

Table 57: Maintenance Activities Impacted by Various Climate Stressors[479]

Maintenance Activity	Heavy Precipitation	Drought	Strong Wind	Lightning	Low Temperature	High Temperature
Replace Signage	•		•	•		
Maintain or Rehabilitate Concrete	•		•	•	•	•
Schedule Crews	•		•	•		•
Clear Drainage	•	•		•		
Repair Embankments	•	•	•	•	•	
Prevent Erosion and Sedimentation	•		•	•		
Excavation	•			•	•	
Fencing	•		•	•	•	
Painting	•		•	•	•	•
Paving	•				•	
Bridge Work	•		•	•		
Maintain Vegetation	•	•	•		•	•

Climate Change Impacts that Affect O&M Activities

The U.S. Department of Labor's Occupational Safety & Health Administration (OSHA) has devoted considerable effort to the avoidance of heat-related worker illness, and most maintenance organizations have dedicated safety professionals and continuous training to guard against heat illness and other threats to worker safety.[480] NOAA heat indices are used to monitor heat exposure and OSHA guidelines are used to regulate activities (see Table 58). As the heat index increases, more protective measures are necessary. For example, low levels of heat index do not necessarily lead to modified work schedules, whereas higher levels might lead to a reduction in the number of working hours on construction projects on a given day.

[479] Source: Meyer et al, 2014 (as modified)
[480] OSHA, 2013a; OSHA, 2013b; and OSHA, 2013c

Table 58: OSHA Guidance for Worksite Modifications According to Heat Indices[481]

Heat Index	Risk Level	Level of Protective Measures	Example Measures
Less than 91°F	Lower (Caution)	Basic heat safety and planning	• Provide drinking water • Ensure that adequate medical services are available • Plan ahead for times when heat index is higher, including worker heat safety training • Encourage workers to wear sunscreen
In addition to basic heat safety and planning, the following is also recommended for higher heat levels:			
91°F to 103°F	Moderate	Implement precautions and heighten awareness	• Alert workers of risk conditions • Remind workers to drink water often (about 4 cups / hour) • Review heat-related illness topics with workers: how to recognize heat-related illness, how to prevent it, and what to do if someone gets sick • Respond to heat-related illness and medical emergencies without delay • Schedule frequent breaks in cool, shaded area • Acclimatize workers • Set up buddy system / instruct supervisors to watch workers for signs of heat-related illness
103°F to 115°F	High	Additional precautions to protect workers	In addition to above: • Ensure adequate medical services are available • Have a knowledgeable person onsite • Establish and enforce work / rest schedules • Adjust work activities to help reduce worker risk • Use cooling techniques • Watch / communicate with workers at all times
Greater than 115°F	Very High to Extreme	Triggers even more aggressive protective measures	In addition to above: • Reschedule non-essential activity for days with a reduced heat index • Move essential work tasks to the coolest part of the work shift; consider earlier start times, split shifts, or evening shifts • Stop work if essential control methods are inadequate or unavailable

Table 59 provides examples of weather-related effects on infrastructure and attendant O&M activities. Relevant impacts to the Gulf Coast (Mobile Area in particular) are noted with an asterisk (*). All of the identified weather-related effects are already impacting locations in the U.S.; however, with shifting geographic climates, new areas are becoming exposed to each of the climate stressors. These areas will have to redirect resources – both financial and personnel – to be prepared to meet these new challenges. In addition to the direct impacts shown in Table 59,

[481] Source: OSHA, 2013b (as modified)

indirect and synergistic climate effects can also be of concern. For example, drought and wildfire conditions associated with climate change can increase sediment loading and cause trees to weaken and contribute to more dead wood in stream valleys. When combined with higher peak flows due to urbanization and increases in heavy precipitation events, the increased amount of dead wood may increase the probability that culverts become plugged. Combined, these stressors increase the likelihood of culverts failing catastrophically during flood events. Similarly, slope slides and rockfalls could increase and tree branches could cause power outages at rates that would otherwise be unexpected under current conditions.

Table 59: Summary of Climate Change Impacts on Maintenance of the Highway System[482]

	Climatic / Weather Change	Highway System Impact Requiring Maintenance	Impacts on Maintenance Work
Temperature	Change in extreme maximum temperature	• Premature deterioration of infrastructure* • Damage to roads from buckling and rutting* • Bridges subject to extra stresses through thermal expansion and increased movement • Closure of roads because of increased wildfires	• Safety concerns for highway workers from heat stress* • Increased attention to pavement failures*
	Change in range of maximum and minimum temperature	• Shorter snow and ice season • Reduced frost heave and road damage • Structures will freeze later and thaw earlier with shorter freeze season lengths* • Increased freeze-thaw conditions in selected locations creating frost heaves and potholes on road and bridge surfaces	• Decrease in frozen precipitation would improve mobility and safety of travel through reduced winter hazards, reduce snow and ice removal costs, decrease need for winter road maintenance, result in less pollution from road salt, and decrease corrosion of infrastructure and vehicles • Longer paving season in colder locations • Increased pothole work* • Vehicle load restrictions in place on roads to minimize structural damage due to subsidence and the loss of bearing capacity during spring thaw period (restrictions likely to expand in areas with shorter winters but longer thaw seasons)

482 Source: Meyer et al., 2013 (as modified)

	Climatic / Weather Change	Highway System Impact Requiring Maintenance	Impacts on Maintenance Work
Precipitation	Wider Range of Precipitation Variability	• If more precipitation falls as rain rather than snow in winter and spring, there will be an increased risk of landslides, slope failures, and floods from the runoff, causing road washouts and closures as well as the need for road repair and reconstruction • Regions with more precipitation could see increased weather-related accidents, delays, and traffic disruptions (loss of life and property, increased safety risks, increased risks of hazardous cargo accidents)* • Closure of roadways and underground tunnels due to flooding and mudslides in areas deforested by wildfires • Increased wildfires during droughts could threaten roads directly, or cause road closures due to fire threat or reduced visibility • Clay subsurfaces for pavement could expand or contract in prolonged precipitation or drought causing pavement heave or cracking • Increasing precipitation could lead to soil moisture levels becoming too high (structural integrity of roads, bridges, and tunnels could be compromised leading to accelerated deterioration)* • Less rain available to dilute surface salt may cause steel reinforcing in concrete structures to corrode • Road embankments at risk of subsidence / heave • Drought-caused shrinkage of subsurface soils	• Increase in blocked culverts* • Removal of debris and other material from roads and roadsides • Need to re-open roads from landslides • Increased erosion from increased rainfall and from burned areas no longer protected from vegetation • Consideration of use of salt and other de-icing materials for varying levels of ice and snow • Possible impact on roadside mowing and handling of vegetation

	Climatic / Weather Change	Highway System Impact Requiring Maintenance	Impacts on Maintenance Work
Precipitation	Increased frequency of intense precipitation, other change in storm intensity (except tropical storms)	• Heavy winter rain with accompanying mudslides can damage roads (washouts and undercutting) which could lead to permanent road closures* • Heavy precipitation and increased runoff can cause damage to tunnels, culverts, roads in or near flood zones, and coastal highways* • Increase in weather-related highway accidents, delays, and traffic disruptions* • Increase in landslides, closures or major disruptions of roads, emergency evacuations and travel delays • Lightning/electrical disturbance could disrupt transportation electronic infrastructure and signalling	• Increase in on-demand maintenance* • Increase in bridge scour protection and response* • Increased attention to road drainage capacity and condition, road evacuation* • Increase in response to electrical outages* • Increase in operations monitoring and response need* • Disruption of planned maintenance work* • Lightning/electrical disturbance could pose risk to personnel, and delay maintenance activity
Sea level rise	Sea level rise	• Higher sea levels and storm surges increase corrosion risk to bridge resulting from decreased freeboard* • Temporary and permanent flooding of roads, underground tunnels, and other low-lying infrastructure due to rising sea levels* • Encroachment of saltwater leading to accelerated degradation of tunnels (reduced life expectancy, increased maintenance costs and potential for structural failure during extreme events)* • Loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action*	• Increase in on-demand maintenance* • Increased attention to drainage structure condition and capacity* • Increased attention to slope stability, erosion in right-of-way, saltwater intrusion to potable water sources* • Increased need for pumping of flooded facilities* • Increase in operations monitoring and response need*

	Climatic / Weather Change	Highway System Impact Requiring Maintenance	Impacts on Maintenance Work
Hurricanes	Increased tropical storm intensity (includes NorEasters and Hurricanes)	• Increased infrastructure damage and failure (highway and bridge decks being displaced)* • More frequent or widespread flooding of coastal roads* • More significant transportation interruptions (storm debris on roads can damage infrastructure and interrupt travel and shipments of goods) • Bridges are more prone to extreme wind events and scouring from higher stream runoff* • Bridges, signs, overhead cables, tall structures at risk from increased wind speeds* • Increased wind speeds could result in loss of visibility from drifting snow, loss of vehicle stability/manoeuvrability, lane obstruction (debris), and treatment chemical dispersion	• Increase in on-demand maintenance* • Increased attention to road flooding, roadside erosion, evacuations* • Increase in operations monitoring and response need* • Increased need for debris removal*

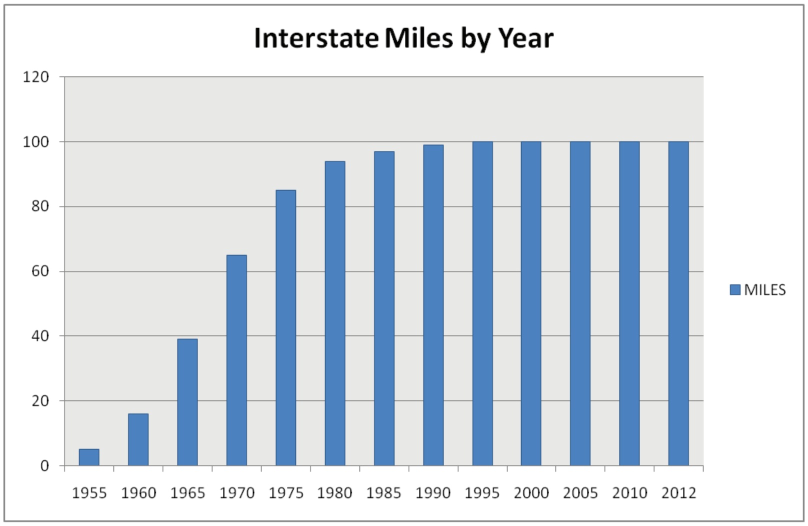
How O&M Activities Can be Adapted to Address Climate Change and Extreme Weather Events

Most of the mid-21st century highway network already exists and is built out.[483] Figure 98, for example, shows the slow pace of interstate mileage added per year since the early 1990s. The highways were constructed with long design lives so the current built out network is anticipated to serve travel demand needs for many years to come. Thus, the focus has shifted from new construction to O&M activities. These activates will account for much of the planning, preparation, monitoring, and response efforts needed to keep the system safe and efficient in the face of climate change. Part of this will include monitoring and forecasting changes in road use demands. Goods movement is likely to increase faster than passenger travel due to expectations of "just-in-time" delivery of goods, causing additional wear and tear to the road network. As mentioned previously, the annual planning and budgeting for O&M activities and the already-routine consideration of weather impacts in decision-making makes it easier to adapt activities, as needed, to prepare for and respond to a changing climate.

O&M activities have always contended with weather and adapted, by necessity, to changes in infrastructure condition, traffic levels, regulatory structures, and (knowingly or not) climate. The ability of organizations to successfully cope with a changing climate (manifested through new and increasingly severe weather patterns) may be limited by more immediate day-to-day concerns. Determining the appropriate role for O&M activities in addressing climate change involves considering what can be done within the confines of budgets, staffing, technology, and available information.

[483] The National Highway System is growing at a rate of only about one quarter of one percent per year, according to USDOT statistics (FHWA, 2010).

Figure 98: Total Interstate Mileage in Existence by Year[484]



Adaptation Actions at the Maintenance Department Level

Despite the uncertainty that remains (and will likely remain for the foreseeable future) with respect to future trends in some climate variables, it would seem prudent for O&M departments to have an understanding of projected climate trends and improve their situational awareness so that they can effectively respond.

General Maintenance Actions

Maintenance organizations can capitalize on experience gained in addressing weather-related infrastructure issues in one or several locations when seeking to proactively increase system resilience to climate change. Maintenance workers often work out of a single residency for the duration of their careers in service to a local constituency. This allows them to have an intimate knowledge of the facilities "owned" by the residency crews, their maintenance history, relative importance, and their resilience to weather events. Depending upon the structure of their work program, this knowledge can be greatly leveraged by integrating it into a transportation asset management system, where asset inventories (includes information about asset type, age, geographic location, etc.) and condition assessments are mapped to facilitate monitoring, performance assessments, risk analysis, and therefore provide necessary information to inform capital and O&M budgeting decisions. The residency organization would, thus, typically be able to provide ready and accurate answers to questions such as, "Which culverts are most likely to fail during a major storm event and which of these would cause the most system disruption?" If their work order system is tied to GIS, they can also usually provide a record of historic failures, repairs, and inspections to better predict the relative risks.

[484] McVoy, Venner, and Sengenberger, 2012

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Analysis of work orders in response to weather events, monitoring of culvert conditions, and tabulation of slope failures can inform future maintenance decisions and be used for budget justifications. Likewise, managers can look for patterns of impacts resulting from climate changes and provide guidance regarding appropriate responses and promote information transfer throughout their organizations. In addition to their work with local residencies, central staff can help ensure that executive agency management is aware of and in support of efforts such as interagency communications and permitting needs that may be required to improve system resilience.

Specific Maintenance Actions

Maintenance forces should consider the following types of actions:

- Consult with designers about more durable materials and designs (e.g., paints, paving materials, drainage features) with consideration for likely future conditions (e.g., higher temperatures, increased rainfall intensities).
- Changing equipment needs due to expected increases in emergency response. It may be increasingly necessary to secure the type of equipment commonly needed in emergencies such as loaders and excavators with "thumbs" for handling woody debris and mobile stock piles of traffic control devices (e.g., cones, signals, signs).
- Stand-by contracts to increase response capacity and shorten reaction times. These contracts may take the form of dedicated response contracts or the addition of "where and when" provisions in all standard and specialized contracts let in connection with the agency's capital program. For example, in preparation for severe weather, ALDOT has local contracts on hand in the case that immediate assistance is necessary.[485]
- Increased identification and monitoring of erosion and sedimentation issues as rainfall intensities increase and climatic conditions change, putting additional stress on ecosystems that evolved under a different climate regime. Consult with designers about need to strengthen both temporary and permanent erosion control best management practices and stream bank protection and scour protection designs.
- Improved weather information systems (sometimes technically known as Road Weather Information Systems [RWIS]), typically employed in snow-belt states, may be applied for year-round use to monitor precipitation and flooding.
- Greater cross-training of staff, perhaps from across the agency, so that the ability to adapt and mobilize for emergency situations is enhanced.
- Stockpiling of materials (e.g., culvert pipe, temporary bridge components, fuel, stone armour) and equipment (e.g., generators, chain saws, traffic control devices). ALDOT stages materials and supplies in different locations in the greater Mobile area, some of which are outside of the storm surge inundation zone, to allow for access even in extreme events.[486] One pipelines operator noted that after a particularly damaging event, all pipelines companies

[485] Powell and Reach, 2012
[486] Powell and Reach, 2012

may be affected, resulting in a high demand for parts. Therefore, some pipeline operators in the region stockpile enough parts to at least temporarily maintain operations while they wait for more permanent solutions.[487]

Permissions, permits, approvals, and contracts as may be needed for debris disposal in the wake of a major storm event.

General Operations Actions

Being responsible for safe and efficient traffic flow, operations has to be able to detect problems through situational awareness, communicate with travelers, and direct other system responses as needed. To accomplish this reliably the operations system must be hardened sufficiently so that it will function during extreme events. In addition to this, the data management capacity of operations can provide valuable information (e.g., flooding locations, tree damage, fog occurrence) that maintenance forces can use as input for the development of their planned activities.

Specific Operations Actions

Some specific recommended operations actions based on current practice include:

- Develop and test a “play book” for emergency operations and, in particular, evacuation protocols.
- Include key stakeholders (e.g., the state emergency operations agency, police, fire, schools, hospitals, government personnel agencies) in routine information dissemination so that all will be in sync during an emergency.
- Cross-train operations staff with maintenance staff to ensure a smooth working relationship has been established before emergency events.
- Harden communications and power systems for emergency use.
- Supplement and adapt ITS resources for disaster monitoring and response.
- Provide detours and signage as may be needed for evacuation.

O&M Adaptation Actions at the Transportation Agency Management Level

O&M activities are carried out in accordance with agency management level policy as specified in budgets, support, and direction. Projects funded by the capital program can help improve climate resilience and decrease system vulnerability, while invariably competing with maintenance funding that can also improve resilience. Funding sources vary, but as a rule both state and federal funding can be used for either purpose. The analysis of capital versus O&M trade-offs (e.g., replacement of a few culverts with capital funds verses the cleaning of many

[487] Powell and Reach, 2012

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culverts under O&M at the same cost) is best done using data driven asset management / risk assessment methods.

While day-to-day O&M activities typically attract little attention, O&M often becomes the center of attention during extreme weather events. Some specific O&M activities that can be undertaken to prepare in advance of an extreme weather event include:

- Conduct planning, design, and construction in accordance with the future demands of O&M. A simple and expedient way to insure this is to require O&M signature approval on contracts and plans that affect a particular district.
- Promote cross training and integrated emergency response both throughout the agency as well as multi-agency training, including ICS and NIMS training. Emergencies quickly become an "agency problem" and the response to them influences public perceptions of the entire agency. If the rest of the agency is not properly trained and equipped, response capacity is effectively limited to O&M staff and the resources they have ready to go. Other departments within an agency can play a role during emergencies relieving some of the burden on the maintenance staff. For example, engineering departments are typically well equipped to conduct activities such as damage assessment and perform best when clearly assigned this responsibility as part of the agency's overall mission.
- Foster integrated interagency relationships with state-wide emergency operations staff, other transportation organizations, first responders, etc. Note that this may be most effective when done at an executive level.
- Design GIS and other information systems to improve the agency's awareness of and response to a changing climate.
- Require tabletop exercises, drills, and scenario development for extreme events.
- Require after-action reports with recommendations for improvement to preparation and response efforts. As applicable, the after-action report should be a coordinated, integrated, multi-agency response in order to capture recommendations from a wide range of skills and capabilities.
- Utilize the knowledge and perspective of the residencies and operations offices in formulating agency-wide climate adaptation action plans.
- Work with local colleges and universities to incorporate maintenance engineering courses into the curriculum.
- Fund, support and equip O&M to handle an increasingly difficult role in adaptation to extreme weather while the competing demands of infrastructure aging and increasing traffic volumes continue to grow.

Design asset management systems and use capital funds to foster improvements in system resilience as described in Table 60.

Table 60: Climate Change Monitoring Techniques and Adaptation Strategies for Transportation Asset Management (TAM) System Components[488]

TAM System Component	Monitoring Technique(s) / Adaptation Strategy(s)
Goals and Policies	• Incorporate climate change considerations into asset management goals and policies, either through general statements concerning adequate attention of potential issues or targeted statements at specific types of vulnerabilities (e.g., sea level rise)
Asset Inventory	• Mapping infrastructure assets in vulnerable areas and responses by maintenance work order (potentially using GIS) • Inventory critical assets that are susceptible to climate change impacts to determine which may be in need of changes in operations or more proactive or frequent maintenance
Condition Assessment and Performance Modeling	• Monitor asset condition in conjunction with environmental conditions (e.g., temperature, precipitation, winds) to determine if climate change affects performance, incorporating risk appraisal into performance modeling and assessment – it is commonly the low intensity, high frequency weather events that contribute to failure rather than extreme events causing catastrophic failure • Identification of high risk areas and highly vulnerable assets through engagement of maintenance forces • Use of “smart” technologies to monitor the condition of infrastructure assets
Alternatives Evaluation and Program Optimization	• Include alternatives that use probabilistic design procedures to account for the uncertainties of climate change • Possible application of climate change-related evaluation criteria, smart materials, mitigation strategies, and hazard avoidance approaches
Short- and Long-Range Plans	• Incorporate climate change considerations into activities outlines in short-and long-range plans • Incorporate climate change into design guidelines • Establish appropriate mitigation strategies and agency responsibilities
Program Implementation	• Incorporate appropriate O&M-related climate change strategies into program implementation • Determine if agency is achieving its climate change adaptation / monitoring goals
Performance Monitoring	• Monitor asset management system to ensure that it is effectively responding to climate change • Consider use of climate change-related performance measures • Establish “triggering” measures to identify when an asset or asset category has reached some critical impacted level that requires O&M

[488] Meyer, Amekudzi, and O’Har, 2010

Utilizing Federal Recovery Funding

When extreme weather events extensively damage the highway systems (as a rule, causing damage totalling more than $700,000), federal aid can be made available to assist with eligible expenses. Recovery funding is typically available for system recovery and restoration through the Federal Highway Administration's Emergency Relief (ER) Program[489] or the Office of Homeland Security's FEMA.[490] Funds are typically initially advanced from other local / state funding sources as needed and later reimbursed through these federal recovery programs. By necessity, both of these programs must cover a wide range of circumstances and require specific documentation and processes for qualification as set forth in FHWA's *Emergency Relief Manual*[491] and FEMA's *Debris Management Guide*.[492]

Federal reimbursement is an integral part of most emergency response plans used by O&M organizations and is best planned in cooperation with the cognizant agencies in advance of any disaster. Note that O&M activities are not always performed immediately following events, but sometimes need to wait for funding or response capacity to become available. For example, port operators in Mobile noted that heavy precipitation can increase runoff and erosion that in turn increase dredging requirements. However, while dredging needs increase with increased precipitation, the frequency and timing of dredging depends on other factors, including budget availability.

Adapting O&M Activities in Mobile

Interviews conducted with state and local officials in Mobile provided a better understanding of the potential impacts of climate change on agency operations in the project study area.

Overview of O&M Departments in Mobile

The City of Mobile has two primary departments related to transportation, Engineering and Public Works, that support O&M activities (including demand activities and extreme weather events). The City Engineering Department consists of about 25 staff members with a primary role in supporting design and development of capital projects and providing technical support to public works. Public Works takes the lead in addressing short orders (e.g., cleaning inlets, fixing potholes). With the help of the City's GIS Department, the Engineering Department is beginning to build asset information on what was funded and fixed. Service requests, for example, can be plotted in GIS and tied to an address.

Mobile County Department of Public Works maintains all County-owned facilities, including an airport on Dauphin Island, 1,379 miles (2,219.3 kilometres) of roads, drainage facilities

[489] FHWA, 2012a
[490] FEMA, 2008
[491] FHWA, 2013
[492] FEMA, 2007a

associated with these roads, bridges, and traffic control devices.[493] In general, the County addresses different O&M needs based on different characteristics of transportation infrastructure (e.g., residential or urban classification of road).

The local ALDOT Maintenance Bureau has responsibility for four southern counties and a fleet of about 140 trucks in the Mobile area. ALDOT is building a new asset management system that will have information on condition (A to F) and other characteristics of each asset. The new system is also expected to be available to cities and counties. ALDOT work orders (assigned work) are generally not required with the exception of any bridge maintenance activities, which are monitored in the Alabama Bridge Information Management System (ABIMS). Work reports (completed work), however, are required for all maintenance activities and can be queried in ALDOT's asset management system.[494]

The operations and engineering department participates in all levels of project review (i.e. 30% design completion; 60% design completion; and plan, specification, and estimate review at 90-95% design completion) and has different standards for culvert designs depending on whether it is an interstate or non-interstate road. Equipment replacement at ALDOT is well-funded and equipment gets replaced on a periodic cycle (defined by years or miles driven). Equipment is viewed as a primary asset and regular replacement has helped reduce maintenance costs.[495]

O&M Adaptation Approaches in the Mobile Area

The Mobile area has the potential to be affected by longer and more intense heat waves, increased intense precipitation events and flooding, higher storm surges, and greater peak wind speeds during the 21st century.

As in most locations, today's maintenance decisions in the Mobile area are often based on month-to-month or day-to-day changes in weather and storm tracks as opposed to anticipated long-term changes. Many O&M actions taken to prepare for extreme events today, however, will yield lessons applicable to future more frequent and / or severe events. For example, sound emergency operations and training have become vital components of O&M programs in this region. Emergency response and operations training occurs annually and is embedded in the work culture. In the event of an emergency, response operations become a collaborative effort among the city, county, and state departments of transportation. Activities can cross jurisdictional boundaries and are National Incident Management System (NIMS)[496] compliant. A variety of O&M extreme weather preparedness actions are underway across ALDOT, Mobile County, and the City of Mobile; these actions will also help prepare for climate change.

[493] Mobile County Public Works, 2013
[494] Powell and Reach, 2012
[495] Powell and Reach, 2012
[496] NIMS, the National Incident Management System, is the organizational system used during emergency events to facilitate coordinated response, communications, and command. See FEMA (2013b) for more information.

The Alabama Department of Transportation

ALDOT is divided into nine different divisions. The Mobile Area is part of the "Southwest Division" which covers the following three districts: District I – Mobile County, District II – Baldwin County, and District III – Conecuh & Escambia Counties. At ALDOT, emergency management has recently become a full time staff position within O&M. As a result, ALDOT has improved and strengthened its relationship with the Alabama Emergency Management Agency and conducts recurring training (e.g., hurricane evacuation exercises) in its divisions and districts. Communication plays a key role in emergency operations at ALDOT. The focus has been on specialized communication equipment that can function independent of cell service in the event cell towers are down to maintain coordination across and between divisions during an event.

Technologies used or considered for use have included:

- Portable Highway Advisory Radios (HARs)
- Satellite phones (under consideration)
- Cameras
- Detection devices
- Dynamic message signs
- Web pages dedicated to road conditions to alert communities (one staff member is dedicated to this)
- A 511 traveler information service that is under development and anticipated to be implemented in January 2014
- Social media (has been considered but not generally used yet due to challenges in QA / QC)

ALDOT also stations equipment and supplies at different locations around Mobile to help speed up how quickly equipment can be deployed and be prepared if one location is inaccessible.[497]

Mobile County and the City of Mobile

Mobile County and the City of Mobile face the same climate challenges faced by ALDOT, but the context and scale of their response differs. Critical infrastructure (e.g., drainage structures) is generally older (often decades older) than that found in the state highway system.

The county and city also must both operate under restricted budgets. The County is constrained by limited funding for equipment repair and replacement, so it is difficult to keep infrastructure in a state of good repair. County crews work four day / 10 hour weeks (from 6:30 am to 4:30 pm

[497] Powell and Reach, 2012

daily), making some of the existing flexible operations options to address extreme heat events difficult (e.g., starting or ending work crew days earlier, providing breaks) without change.[498]

The City of Mobile faces additional challenges associated with working in crowded neighbourhoods and uniquely municipal problems such as litter or debris removal, mature tree preservation, power outages, access, aesthetics, density of infrastructure, and community sensitivity. Further, the economies of scale present in a statewide system in the development of asset management systems, traveler information, worker training, purchasing, equipment, engineering, etc. are simply not available at the municipal level in Mobile and elsewhere.

The following broad-based adaptation planning, preparedness, and recovery strategies were observed in the Mobile area and have relevance to other jurisdictions:

- Run operations like a business. With limited funding, it is important to know which assets or projects are most critical to the safety, reliability, and performance of the system. When possible, develop regular replacement cycles to reduce maintenance costs across all assets.
- Pre-position contracts. This includes contracts for reimbursements from the FEMA and for other contractor work. ALDOT has these vehicles in place for concrete, erosion control, traffic control, striping, etc. where the contractor charges a set rate based on what they bid on plus materials and equipment.
- Position emergency equipment in different locations. Prior to a hurricane or extreme weather event, position equipment like backhoes and chainsaws in different areas, away from locations vulnerable to storm surge for quick deployment. If one location becomes inaccessible, defer to remaining locations to access emergency equipment.
- Maintain good organizational relationships. Communicate well and communicate often. Coordination within the agency, between and across agencies, departments, jurisdictions (e.g., municipal, county, metropolitan planning organization, state), and levels of leadership is necessary. Develop coordination and communication plans and ensure that reliable communication devices are available in the event of an emergency or extreme weather event.
- Drill and train thoroughly and often to insure performance when it's most needed.

Table 61 highlights specific adaptation strategies that are underway or under consideration by ALDOT, Mobile County, the City of Mobile, and others to adapt to projected changes in climate in the Mobile region.

Conclusions

With the National Highway System essentially "built out," O&M activities will play a critical role in efforts to adapt to a changing climate. O&M organizations have always contended with weather-related impacts and adapted to changes in infrastructure conditions, traffic volumes, and regulatory landscapes. Their mission to keep the system in a state of good repair and respond to incidents and emergencies, combined with annual planning and budgeting for O&M activities,

[498] Mitchell and Sanchez, 2013

and everyday consideration of weather impacts in decision making will put O&M staff on the front lines in ensuring the climate resilience of transportation systems. The reality of fixed and finite budgets and the press of other demands besides climate change can make it exceedingly difficult for O&M organizations to be as proactive as they should or would like to be. Advanced asset management systems that integrate climate change monitoring help prioritize the integration of adaptation into O&M activities. O&M personnel in the Gulf Coast region have effectively coped with unique and continuing challenges from extreme weather and climate change and have noted the importance of cooperation and preparation that can help other locations in addressing climate change.

Table 61: Summary of Climate Stressors, Associated O&M Impacts, and Adaptation Strategies Applied or Under Consideration in the Mobile Area

Climate Stressor	Potential O&M Impacts	O&M Adaptation Strategies Applied or Under Consideration
Precipitation Induced Flooding	• Temporary travel disruptions and facility damage	• Stand by and dedicated response contracts to increase capacity • Prepositioning of pumps, supplies, and materials • Regular clearing of drainage ways • Floodway management • Planned detours and response per NIMS
Extreme Heat	• Worker exposure to high heat and possible dehydration • Direct infrastructure impacts - pavements, structures • Stress on equipment	• Have maintenance crews switch to an earlier start time in the summer months • Schedule worker activities to limit prolonged periods of time outdoors • Provide more frequent breaks (e.g., 10-15 minute breaks every hour) • Provision of electrolytes in addition to water • Keep equipment in good repair
Hurricanes / Storm surges	• Direct storm surge inundation of roadways , bridges, tunnels causing temporary travel disruptions, and facility damage • Bridge scour leading to closure of bridge • Loss of utilities including natural gas (affecting pumps and lift bridge) and electric power (causing loss of communications, signal systems, and pumping capacity) with associated travel disruptions.	• Permissions, approvals, procedures and contracts as may be needed for debris disposal and reimbursements • Preparation per NIMS guidance • Position materials and equipment, do staging outside damage area • Plan for FEMA reimbursement • Keep pumps in good repair • Plan for storm proofing tunnels • Harden communications • Have a disaster debris management plan
Wind	• Downing of trees and power lines causing safety hazards and travel disruptions • Breaking of limbs that clog drainage ways and lead to flooding • Breaking of traffic signal wires leading to travel delays • Breaking signs leading to safety hazards and navigation difficulties	• Keep trees trimmed as practicable • Be ready to respond to debris clearance needs • Prepare backup generation and make sure it is ready to go for offices and signals • Put traffic signals on mast arms. • Strengthen sign hardware as it breaks • Supplement and adapt ITS resources to assist with disaster monitoring and response

5. Lessons Learned

5.1 Introduction

The case studies in this report examined the potential impacts of climate change-related stressors on different types of transportation assets in Mobile, Alabama. The case studies hone in on components that are common to transportation facilities across the country (e.g., culverts, abutments, embankments, pavement surfaces, and bridge structures) and across transportation modes. The primary intent of this effort was not to conduct exhaustive technical analysis; rather these case studies aim to establish and demonstrate engineering processes that allow for incorporation of climate change and extreme weather risks into asset-level decision making.

This section summarizes the lessons learned from the case studies presented in Section 4. These "lessons" range from general observations of the process used to determine design values for key input variables (such as expected values of rainfall intensity or storm surge heights), to more specific conclusions relating to the actual design process for particular assets. The lessons learned are based on analysis of specific transportation facilities and projected environmental conditions in Mobile; thus, the engineering design recommendations raised are specific to the site where the facility is located. That said, the lessons learned in this study suggest that strategies are available to help overcome the challenges associated with uncertainties of future climatic conditions; such strategies are transferrable to other projects, locales, and risk management contexts.

The remainder of this section describes:

- Lessons learned with respect to the *General Process for Transportation Facility Adaptation Assessments* (the *Process*), which was the overall approach adopted for the consideration of adaptation strategies on existing assets. The *Process* was also the organizing structure for the case studies.
- Lessons learned on the process for determining the values of key variables used in engineering design that will likely be affected by changing climatic conditions.
- Summaries and findings for each of the facility-specific case studies conducted as part of this assessment.

5.2 Applicability of a General Process for Transportation Facility Adaptation Assessments

Two key lessons emerged as engineers and experts in the kinds of transportation facilities attempted to conduct detailed assessments of facility specific vulnerabilities and adaptation options. The first was the need for some systematic approach or process for incorporating climate and weather risks into standard engineering assessment methodologies. The second was the need for some guidance or examples that practitioners could use to understand and implement this new process.

In recognition of these lessons, the assessments conducted for this study followed a new approach (the *Process*); this served as the organizing framework for each case study assessment and ensured consistency across disciplines and facilities. As described in Section 3, the *Process* incorporates the uncertainties associated with future climatic conditions into an 11-step framework. The *Process* identifies likely vulnerabilities of individual transportation facility assets to climate change and extreme weather variables, examines different adaptation options in light of expected future conditions, and proposes planning and engineering solutions. Importantly, the *Process* was developed as a generic approach to the engineering design of different types of assets under a range of climate change-related variables. The types of design-related questions the *Process* was developed to consider:

- How might environmental conditions change during an asset's design life?
- Will the changes be significant enough to adversely affect the asset?
- What type of adaptation options are available and are they effective?
- If effective, are they cost-effective given the adverse impacts?
- At what rate will changes in climate occur and how may the changes influence the timing of a response?
- How can alternatives be evaluated and/or pursued given the large uncertainties involved in projections of future climate?

Critically important from the standpoint of transferrable lessons, the *Process* does not change the basic variables and design input relationships and procedures that are common to engineering design throughout the United States. The *Process*, as implemented in each case study, does customize the following:

- The values of the climate inputs used in the design methodology;
- The recommended number and type of design options one develops;
- The thought process used to select the final option, which balances cost-effective and resilient transportation services with potential risks.

In particular, three of the steps in the *Process* are relatively new additions to the typical approach toward engineering design:

- Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes
- Step 6 – Identify Adaptation Options
- Step 7 – Assess Performance of the Adaptive Design Option(s)

Step 8 – Conduct an Economic Analysis, while often performed on major projects today, takes on great significance in the *Process* by providing a tool for aiding decision-making in the context of uncertain future conditions. The case studies illustrate how these steps can facilitate incorporation of future climate risks in engineering design.

Judgment will be required by the decision makers as to what assets warrant the use of all or any of the steps in the *Process* when considering improvements to a specific asset or facility. The decision should consider the criticality, the vulnerability, the consequences of failure, and the remaining design life of the asset or facility when determining the design approach.

5.2.1 Lack of Engineering Guidance or Reference Materials for Considering Climate Change

One of the important lessons learned from the engineering case studies is that the 11-step Process can be successfully applied across different types of assets and for a range of climate-change stressors. In fact, the Process was specifically developed to generate consistency among various engineering disciplines working on this project. The Process can therefore serve as an organizing framework for how engineering design can be undertaken considering the uncertainties associated with possible future environmental conditions.

There is an important need for additional guidance on how engineering design can be undertaken given uncertainty about future conditions. Very little guidance and few reference materials are available to provide suggested approaches for considering climate change-related uncertainty in the engineering design process. In developing many of the engineering case studies, considerable discussion and debate occurred among the designers representing different engineering sub-disciplines (including structural, hydraulic, geotechnical and pavement) on the most appropriate approach for analyzing a particular asset given expected future loads and stresses. Engineering practice and indeed engineering culture is focused on research and statistical analyses of historical events (rainfall, extreme heat, etc.); these data provide the required input variables used in decision-making. The uncertainty associated with future input variables that are derived from climate model projections drives the need for a new approaches to develop those input variables and consider their effects when making planning, design, and operations/maintenance decisions.

In recognition of this need, the *Process* was developed to be general enough to be applied to multiple transportation modes and asset types. It can also be used both for *existing* facilities, where adaptive retrofits might be considered, and for proposed *new* facilities where adaptation measures can be incorporated into the design. A rather informal, but important lesson from this study is the cultural difficulty associated with asking engineers to embark on an analysis in the absence of these accepted practices and guidelines. The engineering profession relies on official guidance or design guidebooks for the design process – in part to set a standard of care, facilitate design process consistency and limit potential professional liability based on engineering-supported decisions. In cases where an engineer recommends a design exception based on strong evidence of potential changes in climatic conditions, the exception would require careful consideration and strong justification. Currently, accepted procedures to back up such exceptions are lacking.

5.3 Developing General Input Values for Engineering Designs

A design process that reflects projected changes in climatic conditions has to account for possible changes in the input values of the design variables beyond simply relying on historical data. This is a significant shift from standard engineering design practice.

Engineering designs for transportation facilities rely on a determination of the stresses and loads that facility components will likely face. Identification and determination of the stresses and loads is thus critical to selecting designs that will provide durable and stable asset performance. The engineering profession has developed design procedures and methods that are based on years of experience and documentation of the relationships between load/stress input variables and the resulting design characteristics. For example, one of the most used formulas for determining flow rates for the design of facilities handling rainfall runoff is: $Q = (C)(i)(A)$, also known as the Rational Formula. In this formula, Q is the flow rate, C is a runoff coefficient representing the degree to which ground cover is impervious to water seepage, i is the intensity of rainfall, and A is the drainage area. Thus, the design of a culvert, which is based on the amount of water that is expected to pass through (Q), will depend on the rainfall intensity (i) falling in the area draining into the culvert (A), reflecting the ability of the water to be absorbed by the ground between where it falls and its arrival at the culvert (C).

Traditional engineering design would use historical data for the values of i. In the context of future climatic conditions, however, one might expect that rainfall intensity would change in ways that are not simply an extension of past trends, but may occur at higher/lower rates of intensity more often than has been noted historically. The ground cover runoff coefficient factor might change as well, depending on the location, due to drought, pests, fire, invasive plants due to higher temperatures and/or erosion caused by increased runoff. Thus, a design process that reflects projected changes in climatic conditions in the future would have to account for possible changes in the input values of the design variables beyond simply relying on historical data; this is not unlike designing structures to withstand seismic risks.

5.3.1 Utilizing Climate Data in Engineering Assessments

The engineering case studies illustrated the need to provide input data at a scale necessary for design purposes. This study developed data at the temporal and spatial scale needed to conduct engineering design at the project level but many input variables remain to be translated to useful metrics.

When considering future climate, it is necessary to consider the types of projections that are available and the drivers underlying those projections. In this and most similar studies, the analysis of future climate conditions was predicated on the emission scenarios offered by the IPCC. The IPCC offers a range of emission scenarios that are then used as inputs to multiple

global climate models. Importantly, the IPCC states that each of the emissions scenarios are equally likely to occur;[499] thus, while not providing a different conclusion on any one trajectory of future climate, the climate projections derived from those scenarios are useful in providing a range of outputs that can be considered as a sensitivity test in the planning and design of transportation facilities. A range of variables has been developed that can be used and parameterized in design decisions; some climate data may be found to have no bearing on design while other data may have wide-ranging consequences. The case studies demonstrate that the values of the design variable inputs can have strong influences on expected stresses and loads on transportation assets, as well as on appropriate adaptation response.

The engineering case studies illustrated the need to provide input data at a scale necessary for design purposes. This has been a challenge noted for many years and an identified gap in the application of climate scenario data in engineering design. This study developed data at the temporal and spatial scale needed to conduct engineering design at the project level. Such data were derived from the best climate modeling results available for the region, as well as from assumptions on the best approaches for providing that data that could be used in engineering design.

Earlier tasks of this study included development of climate information (see the Task 2 reports) from which climate narratives were developed (see the Task 3.1 report).[500] “Warmer” and “Hotter” narratives were developed to describe ranges of temperature values, and “Wetter” and Drier” narratives of precipitation projections were developed for the Mobile study region for use in the engineering case studies.

The scenario approach produces a range of values for the input design variables. Depending on the environmental stressors being considered, many of the engineering case studies showed that the scenarios defined by the lower ranges of design input values had either little or no impact on the current design of the asset, or that the impacts could lead to some corrective design action. For those with no impact, the original design of the asset provided enough strength and durability to withstand the forces that were likely to be placed on the asset assuming climate change-induced design values. In other cases, and this was true especially for storm surge, the assets were found to be vulnerable for all scenarios. In fact, with storm surge, in some cases the lower scenario was actually found to be *more* impactful than the higher scenario. This lends further credence to the importance of including lower end scenarios in an adaptation assessment.

5.3.2 Addressing the Design Storms vs. Modeled Future Storms

Rooting future scenarios in the experience of a single historical weather event and then altering characteristics to reflect possible future permutations, has the benefit of providing very relatable results to local stakeholders, especially if a severe storm event occurred recently. However, this

[499] IPCC, 2007
[500] USDOT, 2012; USDOT; 2014

does not allow for the calculation of a return period which presents a challenge when comparing future asset performance against a design standard rooted in return periods (e.g., no overtopping is allowed up to the 100-year storm).

The sea level rise and storm surge scenarios we developed and applied in this study were compiled after coordination with TAC members as well as local stakeholders, and reflect an interest in grounding consideration of future storms in the first-hand experience and lessons learned from Hurricanes Katrina and Georges. Thus, the scenarios considered a number of potential scenarios for storms, including:

- Hurricane Katrina historic storm on its observed path
- Hurricane Georges historic storm on its observed path
- Hurricane Katrina with a shifted path, with its eye making landfall west of Mobile
- Hurricane Katrina with a shifted path, and higher sustained winds

Selected surge and wave models were altered to reflect sea level rise scenarios associated with climate change. These combinations of storms and sea level rise were a subset of the available information generated in earlier tasks, and represented a wide range of outcomes for consideration in the engineering phase of this work. The engineering assessment aimed to understand potential surge impacts on local transportation facilities in the future if a similar storm were to strike again with climate change. Rooting future scenarios in the experience of a single historical weather event and then altering characteristics to reflect possible future permutations, has the benefit of providing very relatable results to local stakeholders, especially if a severe storm event occurred recently.

Engineering practice is based on the premise of "acceptable risk"; acceptable risk is addressed in design standards that hinge on the recurrence probability of storm events (e.g., a bridge designed to pass the 100-year storm with a 1% annual chance of occurrence). Design storms or return period storms are thus a surrogate for an agency's risk tolerance and reflect a trade-off between the costs of providing additional protection to a facility and the likelihood that the event being protected against will actually occur.

As the engineering analysis progressed, the dialogue on surge efforts focused on whether the existing methodology of using the manipulation of a single storm event would be preferable, given that typical derivations of the design storm include a fuller spectrum of possible storm events. It was concluded that the applied method did not provide for the generation of return period probabilities necessary for a probabilistic analysis, but presented options for assessing impacts for some selected and relatable storms. This presents a challenge when applying the surge projections to some engineering assessments because comparing future asset performance against a design standard rooted in return periods (e.g., no overtopping is allowed up to the 100-year storm) is not possible. Understanding performance relative to a return period storm is important to established engineering practice. It is also key to fostering a dialogue on risk

because without some projection of how event probabilities may change over time no formal assessment of benefits and costs can be made in the manner that was done for the culvert case study.

Defining the storm surge scenarios based on different greenhouse gas emissions scenarios and determining changes to surge elevations of the design storm of interest (e.g. the 100-year storm) under each scenario would address this challenge. This was the same general approach employed on the culvert study for precipitation depths whereby a future 100-year storm precipitation depth, for example, was generated and compared to today's value. That said, as noted in Step 4 of Section 4.4.4, generating accurate future surge return periods could be a very expensive undertaking that will require considerable modeling efforts and statistical analysis on par with those employed by FEMA to develop the current return period values. Such analyses are likely to be well beyond the resources available for many individual transportation projects and will likely need to be done as part of nationwide, state, or regional undertakings by FEMA, USACE, NOAA, or other pertinent agencies. As such this information is not likely to be available for the foreseeable future for transportation project design, and a simpler alternative approach will likely have to suffice in the interim.

One simpler approach could involve adding sea level rise to the existing return period surge elevation of interest and deriving a new return period event in that manner. However, this "bath tub" approach would need to acknowledge that it only considers the sea level rise component of climate change impacts on surge (changes to storm intensity and frequency would not be accounted for, as there is less understanding of climate's impacts on these factors) and it does not account for the non-linearities that changes in water depth engenders on surge elevations and wave heights. A somewhat more sophisticated approach that would address the aforementioned non-linearity issue would involve identifying the elevation of the current return period event of interest and then conducting localized surge and wave modeling of that event coupled with sea level rise. The process used in this study – based on specific historic events combined with alterations to reflect projected future conditions – was the best option available, but additional research and dialogue to identify and refine future surge scenarios for use by engineers in design is needed.

5.3.3 Downscaling Climate Scenario Data for Engineering Design

The engineering case studies illustrated the need to provide input data at a scale necessary for design purposes. This study developed the best available projections at the temporal and spatial scale needed to conduct engineering design at the project level, subject to the limitations inherent in developing projections of future temperature and precipitation values relevant to engineering design.

Obtaining data at the appropriate scale has been a challenge noted for many years and an identified gap in the application of climate scenario data in engineering design. In some cases,

the results of climate models are appropriate to do engineering design. For example, the design of large culverts can use 24-hour precipitation values that are generated from climate models. In other cases (e.g., the design of small culverts) engineers need precipitation data that occurs in shorter time periods, which has traditionally been represented with intensity-duration-frequency (i-d-f) distributions with less than 24-hour values. Global climate models and regionally downscaled projections can provide hourly values, but often this data is summarized and made available at the daily, weekly, monthly or seasonal level of aggregation to provide a greater level of robustness.

Further discussion of the processes identified here and other methodologies for applying derived climate data will be of great value in developing future values for precipitation and temperature at the level where engineers can apply them at the project level.

5.3.4 Considering the Full Range of Climate Change Scenarios

It is important for a robust design process that a range of climate change-related variables be considered, simply to make sure that even the lower estimates do not require corrective design action, and that a reference alternative is presented for the scenario analyses of the higher stresses on the assets. Additionally, in some cases the lower scenario was actually found to be more damaging than the higher scenario.

The scenario approach produces a range of values for the input design variables. Thus, for example, the "Warmer" narrative produced a lower temperature average and a different range in high/low temperatures than the "Hotter" narrative. Similarly, the scenarios relating to storm surge resulted in different surge heights.

Depending on the stressors being considered, many of the engineering case studies showed that the scenarios defined by the lower ranges of design input values had either little or no impact on the current design of the asset, or that the impacts could be addressed through corrective design action. For those with no impact, the original design of the asset provided enough strength and durability to withstand the forces that were likely to be placed on the asset assuming climate change-induced design values. For example, the pavement design case study determined that under the "Warmer" narrative, temperature changes were not great enough to require any adaptation from current practice through 2100.

In other cases, and this was true especially for storm surge, the assets were found to be vulnerable for all scenarios. In fact, with surge, in many cases the lower scenario was actually found to be *more* damaging than the higher scenario. In many cases it is the wave action that is likely to cause the most damage to a facility and once a facility is submerged (which is more likely in a higher surge scenario), the wave impacts are actually reduced. This was the case, for example, in the studies on the ramp between the Causeway and the Bayway Bridge and on Dock One at McDuffie Terminal. This lends further credence to the importance of including lower end scenarios in an adaptation assessment.

5.4 Facility-Specific Lessons Learned

Engineering design practices are very specific to different asset types, and the considerations of environmental factors in engineering design will reflect the site-specific context. In this study, we have focused on example facility-impact relationships in order to understand those specific relationships and adaptation options. However, in analyzing adaptation options for a specific facility, it is important to consider all impacts a facility might face, not just for example SLR or surge or precipitation-induced flooding. The following sections describe the lessons learned for the different assets.

5.4.1 Culvert Exposure to Changing Precipitation Patterns

This case study of the Airport Boulevard culvert over Montlimar Creek demonstrated how a large culvert can be analyzed for a projected increase in precipitation. Adaptation options were identified and tested using a benefit-cost framework.

The analysis found that the culvert would not meet ALDOT standards on culvert design[501] under the future precipitation levels assumed for this analysis. That is, under feasible future climate conditions, the roadway could be overtopped during the 25-year storm events. To address this problem, the analysis considered two options for increasing the capacity of the culvert: adding one cell on each side of the existing crossing, and replacing the existing crossing with a larger one. Taking into account both the expected performance and the cost-benefit of each option, the study indicates that adding one cell on each side of the existing crossing (Option 1) is the preferred course of action, as it is effective, lower cost, and most likely to be cost-effective. The case study also showed that there are likely to be substantial costs incurred if no adaptation actions are taken to address expected flooding at the culvert.

This case study yielded some important lessons learned that are more broadly applicable to similar analyses. One lesson is that the use of 24-hour duration precipitation projections that are available from standard climate models is an appropriate approach for designing large culverts. The resulting adaptation design for the case study culvert was based on accepted engineering practice for determining runoff rates and resulting headwater elevations. For smaller culverts, however, where 24-hour projections *may* not be applicable, one is more likely to use the Rational Formula (described earlier) with input from intensity-duration-frequency (i-d-f) curves for which downscaled climate model data is not readily available.

This case study also demonstrated how a Monte Carlo analysis can be an effective way to deal with the environmental uncertainties influencing major projects. The analysis simulated thousands of different combinations of precipitation events under five climate/land-use scenarios

[501] ALDOT standards require that the 25-year flood be used for design of waterway crossings on secondary routes such as Airport Boulevard. The standards also require a minimum of two feet (0.6 meters) of freeboard[501] above the design flood stage (relative to the edge of pavement) to keep the water surface an adequate depth below the pavement base. See page 54-55 for more information. (ALDOT, 2008)

and then estimated the resultant flooding costs over a 30-year appraisal period. This approach was very useful in considering future climatic conditions that could affect the performance of the culvert and therefore of the benefits associated with adaptation options.

Another lesson learned is that benefit-cost analyses of adaptation options are greatly influenced by what is included within the bounds of the analysis. When considering only travel time costs associated with road crossings, the benefit-cost analysis supported selection of the less expensive Option 1. However, when one also considers the potential damage to buildings and businesses that could be damaged under a "Wetter" narrative, the benefit-cost analysis supports selection of Option 2, (replacing the culvert) because the additional damage costs more than offset the additional costs associated with building the second option. It is up to the analyst to determine which benefits will be included in the analysis; however, the case study does suggest a need to consider benefits beyond the road right-of-way.

Finally, the case study did not examine the impact of downstream increases to flow and attendant land use impacts associated with increasing the culvert capacity. When such analyses are conducted for a project, additional detailed hydrologic analysis would be required.

5.4.2 Bridge Over Navigable Waterway Exposure to Sea Level Rise

This case study of the Cochrane-Africatown USA Bridge examined whether a coastal bridge could limit navigation on the tidal Mobile River as a result of projected sea level rise. The U.S. Coast Guard requires a minimum vertical clearance of 140 feet. This analysis considered whether this minimum vertical clearance would still be met under the following sea level rise scenarios:

- One foot (0.3 meters) of global sea level rise by 2050
- 2.5 feet (0.8 meters) of global sea level rise by 2100
- 6.6 feet (two meters) of global sea level rise by 2100

The analysis found that the navigation requirements for the bridge would not be violated under the first two sea level rise scenarios. However, a sea level rise of 6.6 feet (2 meters) by 2100 would, over time, reduce vertical clearances such that navigation is impeded. In addition, bridge structural corrosion might be accelerated, and in some cases, the bridge itself (or its approaches) may become permanently inundated. On a broader scale, the case study showed that there are many options that could be considered to adapt to rising sea levels. Some options focus on structural changes to the bridge, such as raising the bridge deck, redesigning for a thinner deck and shorter spans, or retrofitting the bridge with moveable spans. For bridges with navigable spans that might cause significant navigational impacts due to sea level rise during their design lives, future bridge rehabilitation analyses should consider options to reduce navigation clearance-related impacts such as elevating the deck. Investigation of how substructures can be extended, modified, or completely rebuilt will need to be done at the time of rehabilitation on a case-by-case basis. Future modeling should be considered to ensure that whatever option is chosen takes into account the latest sea level rise trends. In cases where the design life of a

bridge is short enough that expected sea level rise would not affect it during its design life, it might very well be the case that an eventual full replacement of the existing structure with a design that accounts for anticipated sea level changes will be a more cost-effective solution than retrofitting the existing structure now.

Other options relate to the broader use of the river, and the infrastructure around it. For example, it could be accepted that vertical clearance would be gradually reduced and larger vessels would not be able to navigate past the bridge in the future; ports requiring access to larger vessels could eventually be relocated downstream, or routes with lower bridges could eventually be located upstream of ports.

As sea level rise is a relatively gradual phenomenon (even considering its projected acceleration after mid-century), time will allow for continual evaluation of changes in actual sea levels. Monitoring of sea level rise trends compared to design life depletion rates should be conducted to help determine the optimal scheduling of an adaptation solution. As 2100 approaches, it might be that the actual sea level rise is not near the assumed analysis value and that no adaptations will be required. In the case of the Cochrane-Africatown USA Bridge, the likely trend in sea level rise might become apparent by mid-century and a decision could be made then on how to proceed.

Given the wide range of feasible adaptation options, port and transportation planners should begin monitoring sea level rise as its potential constraints on navigation as soon as possible. It may be decided that immediate action is not needed, but understanding future constraints could be factored into decisions related to siting of port facilities and upcoming bridge rehabilitation processes. Continued monitoring will allow decision makers to reassess their selected course of action as better information on future sea levels becomes available.

Finally, the case study did illustrate that the *Process* is broadly applicable to bridges across the country where sea level rise has an influence. Bridges over navigable channels would need to be investigated for clearance reductions due to sea level rise and determine if any remedial action would need to be implemented. Ultimately, this effort is best handled at a planning level in a coordinated manner amongst all bridges along a shipping channel. Adapting one bridge to accommodate sea level rise without consideration of adapting other bridges along the channel may impede access.

5.4.3 Bridge Approach Embankment Exposure to Sea Level Rise

This case study of the US 90/98 Tensaw River Bridge western approach showed how sea level rise effects on wind-generated wave heights and wave impacts could be analyzed for an approach roadway embankment. In particular, sea level rise can contribute to increased wave heights and energies impacting embankments, which in turn can cause increased scouring and erosion, potentially affecting the stability of an embankment.

This case study showed that embankments assessed are susceptible to sea level rise and wind-generated waves. The progression of sea level rise and its impact on sustaining taller waves could present challenges for maintaining the functionality of a roadway embankment. Under each of the climate scenario narratives in this case study, protection and risk reduction measures would be needed for the embankments. Specifically, the roadway and abutments would need to be raised to a height that would significantly reduce the risk of overtopping from wave run-up. As sea levels rise and water depths in front of an embankment increase, the height of waves that can be sustained without breaking prior to impacting the embankment increase, consequently increasing the weight and dimensions of the riprap needed to protect against them. In addition, as the wave size increase, the height at which the run-up impacts the embankment and approach roadway increases as well.

It is important to note that this analysis showed that, under the three sea level rise scenarios considered, the bridge itself was not overtopped but the approach roadway located west of the abutment was susceptible to flooding. This finding is important because it supports other studies that have found that bridge approaches can be far more vulnerable to sea level rise than the main spans. Long before the actual bridge is overtopped, its approaches may be overtopped, making the bridge unusable.

This case studied notes that, when considering protection measures for this type of asset, potential stressors upon the abutment must be taken into account—including storm surge events. This analysis considered only the effect of sea level rise on wave heights and velocities, but sea level rise could also magnify the impact of storm-related surge events.

The general analytical methods demonstrated here can be applied to other coastal embankments, including causeways, coastal roadway embankments parallel to shorelines, or barrier island roads that are (or may become) subject to regular wave impacts due to increases in sea levels.

5.4.4 Bridge Abutment Exposure to Storm Surge

The combination of sea level rise and potentially more intense storm surges enhance the threat of potentially devastating impacts of coastal bridges. This case study examined how a bridge abutment can be analyzed for storm surge scenarios, using the elevated ramp leading from US 90/98 to I-10 (the west abutment of the US 90/98 Tensaw River Bridge) as an example.

The review concluded that while the abutment itself was not designed to be stable under scour conditions, the protection components of riprap, bulkhead, and willow mattress were so designed. The combined considerations for the abutment and the protection scheme showed that the system was stable and capable of performing for the current conditions and each of the projected surge events.

From a methodological standpoint, an interesting finding is that peak velocity of the surge does not coincide with the peak water surface elevation. Due to the bi-directional nature of coastal

surges (flood and ebb surge), it was found that the peak velocity occurred at two points, first during the flood surge and later during the ebb surge. The peak velocity for each of these conditions occurred when the rate of water surface elevation change was at its greatest. In this case study, the abutment scour and protection computations were performed for the flood surge peak velocity, the controlling velocity for scour analysis. This would likely be the case for many other scour analyses in coastal environments.

The analysis highlighted the important role that protective features play in the resiliency of an asset. The abutment analyzed in this study was not designed in consideration of full abutment scouring conditions; in lieu of other protection factors, the abutment could be reasonably expected to fail. However, the presence of protective features (riprap, willow mattress pad, and a timber bulkhead) provide enough protection that the abutment would likely be able to withstand the surges analyzed. This finding is neither unique to this bridge design nor unexpected. Given the widely held view that abutment scour equations produce overly conservative results, many state agencies have chosen to armor or otherwise protect abutments from scour rather than design the foundations for the full scour depth. The lesson learned from the multi-protection strategy was that a combination of engineering options can be used to protect against scour from storm surges. Furthermore, inspectors should be informed that even if the structural portion of an abutment is situated on “dry” ground, other components such as bulkhead, riprap, or other stability measures may play a key role in the overall scour resistance of the abutment and should likewise be monitored.

5.4.5 Bridge Segment Exposure to Storm Surge

This case study of the US 90/98 ramp to I-10 eastbound at exit 30 demonstrated how a bridge can be analyzed for potential storm surge scenarios, including where sea level rise has been factored in. Using increasingly severe storm scenarios (with and without sea level rise), the analysis considered whether the bridge was susceptible to three different modes of failure: (1) the superstructure (e.g., deck) is uplifted by waves and washes away, (2) the substructure (e.g., bents, pier caps) fails due to lateral forces from waves, or gets uprooted from vertical forces acting on the superstructure, and (3) the substructure fails due to excessive scour.

The bridge analysis found that both the superstructure and the substructure could fail under the storm scenarios investigated. At specific bents, the superstructure could have bolt failures at the bottom of the girders and lift off and wash away. Meanwhile, the piles have sufficient axial capacity to resist the uplift force on the superstructure (up to the point the anchor bolts on the superstructure fail), but may not able to resist the lateral forces (shear and moment), and could fail due to shear and/or bending.

However, these results are not consistent with what actually occurred during Hurricane Katrina, which caused superstructure damage but did not damage any of the piles. This discrepancy is likely due to the fact that detailed geotechnical data—such as the shear strength parameters and

physical properties (e.g., plasticity characteristics, unit weight) of soils—was lacking. The lesson here is that these analyses are very sensitive to the quality and completeness of the inputs. As with any actual project, a full analysis of the site should involve field collection of geotechnical data (i.e., soil borings) if this information is not already known.

When considering ways to make a bridge more resilient to storm conditions, transportation offices could consider a design that would allow the superstructure to break away during a significant storm surge so that the substructure would remain intact. Although bridge would have technically "failed" under this situation, rebuilding the bridge would take less time and be less costly than if the substructure was damaged. In essence, the facility would be designed for a controlled failure if surge and wave forces become too great. A complementary adaptation measure would be to ensure that superstructure design documents be safely stored and made easily accessible after an event, so that the replacement could occur quickly. When considering controlled failure as an adaptation strategy, it would be important to consider the community needs served by the bridge, and whether the community can continue to function well if use of the bridge is temporarily lost. If not, then more aggressive protection measures may be warranted.

This analysis also found that the worst case storm surge scenario does not necessarily translate to the worst effect on the facility because the contours of the ground surface beneath the water body can influence current strength and direction, as well as wave height.

5.4.6 Road Alignment Exposure to Storm Surge

This case study of I-10 (from mileposts 24 to 25) examined how a road or rail alignment can be affected by surge flooding combined with sea level rise. The assessment considered the potential for:

- storm surge to overtop the I-10 roadway and underpasses,
- the I-10 roadway to breach due to overtopping flows,
- flooding to impact the nearby neighborhood of Oakdale, and
- the implications of flow velocities through the underpasses at the three bridge crossings.

The case study found that all of the storm surge scenarios tested present some threat of inundation and erosion to the roads and railroad passing through the underpasses in the study corridor. I-10 would be expected to overtop in the more severe surge scenarios (but not in the Katrina Base surge scenario), and some of the underpasses could flood in all three storm scenarios.

The roadway could breach due to overtopping flows in the two more extreme storm scenarios. It was estimated that the Hurricane Katrina Shifted Scenario storm surge could cause failure of the shoulder lane and four travel lanes on both sides of the roadway. The Hurricane Katrina Shifted

+ Intensified + SLR Scenario storm surge could result in breaching of the entire width of the roadway.

The case study showed that the neighborhoods surrounding the roadway facility would be impacted by storm surge that is funneled through roadway underpasses. The I-10 roadway embankment would not provide a significant barrier to the surge waters entering the Oakdale neighborhood.

The evaluation of the flood velocities through the underpasses indicated that, since all three bridge crossings within the study site have concrete abutments and concrete roadways under the bridges, the majority of the roadway is protected from erosive flow velocities for all storm surge scenarios. However, small sections of the median that consists of soil and grass could be affected by erosive flow velocities; this finding is significant because the bridge piers are located in the grass median. Finally, the rail line under one of the underpasses may be vulnerable to the flow velocities analyzed.

An important lesson from this case study is that additional erosion protection should be considered when designing roadway crossings that could be subjected to reverse flow from storm surges. Certain materials (such as concrete) are less vulnerable to erosive flow (such as soil grass), and the selection of building materials could influence the vulnerability of roadway crossings.

Another important aspect of an analysis of roads in coastal areas is that roadway pavement drainage could be impacted by increased precipitation intensity as well (in addition to the storm surge factors analyzed in this study), where the flat slope of a roadway may not meet the design spread conditions for a given precipitation event because of its location. A roadway drainage system could be impacted by both increased precipitation intensity and by increasing water levels at the system outlet (tail water) due to storm surge. This will likely decrease the ability of a drainage system to handle water flows.

Another important finding is that changing the width of the underpasses may not prevent storm surge from entering a community. The analysis showed that widening the underpasses does not increase the volume of storm surge flows entering the Oakland neighborhood because the existing underpasses are already capable of conveying the storm surge flows inland without significant attenuation. Widening also does not significantly reduce the maximum velocities through the underpasses.

Further, at this specific site, raising the roadway does not help to prevent storm surge flows from entering the neighborhood.

Thus, the adaptation options proposed (widening the underpasses and raising the roadway) do not significantly alter the amount of flooding in the neighborhood.

5.4.7 Coastal Tunnel Exposure to Storm Surge

This case study of the Wallace Tunnel[502] examined a tunnel's vulnerability to storm surge-related flooding during a hurricane and the additional protection provided by various adaptation modifications. The analysis relied upon a three-step modeling procedure to develop quantitative estimates of the risk of flooding in the existing tunnel. The use of this modeling procedure underscores the need in adaptation analysis to select appropriate, high-fidelity, storm surge and wave computer models and to include experienced coastal engineers on the study team. One of the primary lessons learned was that when evaluating the impacts of storm surge, wave height must be included in the analysis; otherwise, the tunnel could flood due to wave overtopping some of the portal walls even when the storm surge elevation is below the wall crest elevation as found in the study of the Wallace Tunnel. A second lesson learned from this case study was that the most commonly understood measure of storm strength - the Saffir-Simpson Hurricane "Category" Scale - was not particularly valuable for engineering decisions. There is no one-to-one relationship between storm surge and storm "category." The fact that commonly used measures to describe extreme weather events are not readily used in engineering design processes is not true only for tunnel and potential flooding analyses. It represents an important challenge to engineering design for extreme weather conditions.

A final lesson learned relates to the adaptation design options. Seemingly logical design options may not effectively achieve the goal of protecting the tunnel from flooding. Increasing the portal wall elevation just to account for storm surge alone would not have increased the level of flood protection much. One must consider wave impacts on top of the surge levels at the more exposed portals. Along with this broadened consideration, the adaptation design process also needs to include some iteration or "feedback-loop" process such as the search for more effective alternative design options as was done in the case study.

5.4.8 Shipping Pier Exposure to Storm Surge

Dock One at the McDuffie Coal Terminal was analyzed to determine the performance and survivability of the dock against environmental loads associated with sea level rise and storm surge.[503]

This case study determined that the likelihood of the pier structure performing well under all three climate scenarios was very high. The reason is that industrial piers like the one at McDuffie are designed for very large loads. They tend to be very robust and able to stand environmental forces. Berthing and mooring loads are typically much greater than the loads caused by storm conditions; thus, a pier designed to withstand berthing and mooring loads should be able to withstand storm surge loads and in fact, there are no code requirements with regards to storm

[502] Based on the study *Storm Surge Analysis for the I-10 Tunnel* performed by Douglass et al. (2007) on the I-10 tunnel under the Mobile Ship Channel.
[503] Only the main pier structure was analyzed. In a comprehensive analysis, other features at this location would also be examined, e.g., the mooring dolphin, and mooring dolphin access walkway, electrical equipment, and mechanical equipment.

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surge for facilities like Dock One for this reason. Historically, the survivability of these types of structures has been very high during storms.

The key weakness in terms of survivability to increased loads occurs at locations where different asset elements are connected. For example, the walkway connecting the pier to the shore is anchored at both the main dock and at each pile bent cap beam by anchor bolts either drilled or cast in concrete depending on their location to resist uplift. These anchorages also survived the lateral loads applied due to surge and waves for each of the scenarios analyzed. However, similar facilities in the region do not have these anchorages and would be more vulnerable to the surge scenarios analyzed. Additionally, where these connections exist, such as at Dock One, they should be inspected regularly and evaluated for their capacity to withstand loading from the proposed climate scenarios. This would include all areas requiring anchorages such as access walkways.

This observation also suggests the need for asset condition monitoring. When conducting climate change analyses of existing pier facilities, a thorough understanding of the facility's condition must be factored into the analysis. Information such as condition assessments, load ratings, and structural inspections should be consulted and, if not available, new inspections of the facility should be undertaken.

Finally, while the dock structures at industrial facilities will typically survive surge events, the same cannot always be said about the equipment and ancillary assets associated with pier operation. A full analysis of a port facility should consider all components of port operations including equipment, storage facilities, and access routes.

5.4.9 Pavement Mix Design Exposure to Temperature Changes

This case study examined the current pavement design practices of ALDOT and analyzed how climate change might affect mix designs of both asphalt and concrete for new highway facilities. Specifically, the effect of higher temperatures on the pavement in Mobile was evaluated, since temperature change is the key environmental factor affecting pavement performance. The focus of the case study was to evaluate how to help prevent premature pavement design failure from on joint cracking and rutting.

The most important lesson from this case study is that, while the current performance grades specified locally are adequate, higher temperatures may require adaptation strategies for pavement design, for example, under the "Hotter" narrative, temperature increases are projected to become great enough by mid-century that adaptation options should be considered. A variety of possible adaptation options were provided for coping with projected temperature changes under the "Hotter" narrative, including moving towards asphalt binders rated for higher temperatures and coarser aggregates.

For concrete pavements, modern specifications should account for the use of improved materials in order to ensure improved concrete performance under all placement conditions. To provide improved performance for sections paved under hot weather conditions, one option could be to revise the continuously reinforced concrete pavement (CRCP) reinforcement standards so that they provide steel quantities for specific use during hot weather conditions, and also to revise the specifications to limit the maximum in-place concrete temperature during hydration.

Finally, this case study found that there is very little information in the professional literature on the impact of climate change on pavement materials. Pavement engineers, with assistance from government agencies and climate change experts, should be encouraged to develop a protocol or guide for considering potential climate change in the development and evaluation of future designs. The guide should extend beyond the narrow focus on pavement mix design in this case study to incorporate all elements of climate change impacts on pavement design (e.g., sub-base, drainage, pavement texture). Researchers should explore if and how the AASHTO Ware Pavement Mechanist Empirical (ME) Design® software can be adapted to incorporate climate change. Amending the software to incorporate climate change projections would be a logical next step in its development.

5.4.10 Continuous Welded Rail Exposure to Temperature Changes

If rail temperature is not properly considered in the laying of track, the track structure can become disturbed in periods of extreme heat or cold, requiring maintenance expenditures, causing train delays, and leading to a heightened risk of derailments. This case study examined the impacts of projected temperature changes on new track laying and maintenance of way practices. The focus was on continuously welded rail (CWR). Unlike for other case studies, it was not necessary to select a specific segment or asset, so this case study evaluated the impact of higher temperatures on CWR in Mobile generally.

Specifically, the analysis considered the impact that changing climate conditions would have on determining the neutral temperatures, which is the rail temperature that would result in zero thermal stress on the rail itself (i.e. result in neither expansion nor contraction). Neutral temperature is a key factor in determining how to lay rail, and this analysis examined how increased ambient temperatures could affect the neutral temperature (which is measured as the temperature of the rail itself).To assess the impact of on the, this case study considered the relationship between the maximum and minimum ambient air temperature (as output from climate models) and actual rail temperatures.

The case study found that the neutral temperature used by the railroad (100ºF or 37.8°C) would be inadvisable under the “Hotter” narrative at all future time periods. Continuing to use the adopted neutral temperature might increase the risk of sun kinks in the future. However, the current neutral temperature would still be adequate under projected temperatures of the

"Warmer" narrative. Thus, whether or not the current neutral temperature is adequate for the future depends on the assumed changes in future temperatures.

The case study also found that there are very limited options for handling temperature-related threats. The primary adaptation action that could be taken on new CWR track would be to increase the rail neutral temperature. Alternately, ballasted tracks could be constructed and maintained with a minimum of one foot (0.3 meter) wide shoulders to provide lateral support to the ties.

5.4.11 Operations and Maintenance Activity Exposure to Climate Change and Extreme Weather Events

Operations and maintenance (O&M) activities address such challenges as the aging of the infrastructure and the impacts of increasing traffic volumes as well as the significant stress that extreme weather events place on the transportation system. Heavy precipitation, lightning, and strong winds affect operations and maintenance activities. Severe storms will disrupt most O&M activities and even a light rain or moderate wind can be enough to delay activities like painting or sign replacement. In addition to such direct impacts, indirect and synergistic climate effects can also be of concern. For example, drought and wildfire conditions associated with climate change can increase sediment loading and cause trees to weaken and contribute to more dead wood in stream valleys, resulting in clogged culverts. This case study examined how weather and climate may influence current O&M activities and how those activities may be adapted to reduce the vulnerability of transportation systems to weather and climate-related risks.

Because Mobile has historically experienced extreme weather events, their community and transportation agencies have developed important best practices that could be employed by other communities expected to experience more extreme events in the future. First and foremost, O&M personnel in the Gulf Coast region need to be prepared for the unique and continuing challenges of extreme weather, particularly when it comes to cooperation between organizations. In Mobile, emergency operations and training have become vital components of O&M programs. Emergency response and operations training occurs annually and is embedded in the work culture. In the event of an emergency, response operations become a collaborative effort among the city, county, and state departments of transportation.

Other best practices include:

- Have a tested "play book" for emergency operations and, in particular, evacuation protocols.
- Include key stakeholders (e.g., the state emergency operations agency, police, fire, schools, hospitals) in routine information dissemination so that all will be in sync during an emergency.
- Pre-develop contracts so that reimbursements from FEMA can be easily processed. ALDOT has these vehicles in place for concrete, erosion control, traffic control, striping, etc. where the contractor charges a set rate based on what they bid on plus materials and equipment.

- Pre- position emergency equipment like backhoes and chainsaws away from locations vulnerable to storm surge prior to hurricanes or other extreme weather events for quick and flexible deployment so that if one location becomes inaccessible, equipment may be available from others.
- Cross-train operations staff with maintenance staff to enhance their working relationship during emergency events.
- Work with local colleges and universities to incorporate maintenance engineering courses into the curriculum**.** A lot of on-the-job training is required to get engineers prepared for extreme weather events and emergencies. Maintenance engineering classes at the college or university level would help prepare entry level engineers and improve their understanding of what they can expect to experience when they start working for a city or DOT.
- Harden communications and power systems for emergency use.
- Supplement and adapt ITS resources for disaster monitoring and response.
- Provide detours and signage as may be needed for evacuation
- Keep the system in a state-of-good-repair.
- Work resilience into the asset management system.
- Budget and plan for extreme events. Run operations like a business. With limited funding, it's important to know which assets or projects are most critical to the safety, reliability, and performance of the system. When funding becomes available, you'll know where and how to direct funds. When possible, develop regular replacement cycles to reduce maintenance costs associated with aging equipment.
- Communicate well and communicate often**.** Coordination within the agency, between and across agencies, departments, jurisdictions and levels (e.g., municipal, county, metropolitan planning organization, state) of leadership is necessary. Develop coordination and communication plans and ensure that reliable communication devices are available in the event of an emergency or extreme weather event

5.5 Conclusions

The engineering case studies, and the process of developing the inputs that are used in this design process, have shown that climate-change related factors can be successfully incorporated into the engineering design process. The *General Process for Transportation Facility Adaptation Assessments* used here has been shown to be a useful approach for considering the uncertainties associated with future environmental variables, and as an organizing concept for adaptation engineering studies. The case studies also showed the lack of available technical guidance for conducting adaptation engineering, and the barrier this represents to many engineers who rely on accepted practice for the design approach.

Data is always a key issue when considering the design of a facility. Engineers want to provide a safe, durable, and stable facility that will withstand the stresses and loads coming from the environment and from the use of the facility itself. When considering the uncertainties associated with the future values of design parameters with different climatic conditions, credible and

defensible values for design inputs become even more of a challenge. The approach illustrated in this study has been to use climate narratives that represent possible future conditions that become the input to the design process. These narratives provide a range in the level of stress that is placed on different types of assets for different climate-related variables. Given that the ultimate design will reflect the values of the design parameters utilized in the design process, great care must be taken in defining the scenarios that are used and consideration of the cost and practicality of the adaptive designs.

Finally, and perhaps most importantly, the engineering case studies showed that many of the assets analyzed in the Mobile study area were indeed vulnerable to changing environmental conditions. Whether due to storm surge and wave action combined with higher sea levels or higher temperatures, the assets as currently designed in accordance with accepted current design approaches may not withstand some of the stresses that might occur given a changing climate. There is a strong need to provide technical guidance and design methods to account for such uncertainties as the nation builds new infrastructure or rebuilds existing infrastructure.

6. Future Research

6.1 Introduction

This section identifies research that is needed to better understand the implications of climate change and extreme weather events on transportation infrastructure. Similar to the prior section on lessons learned, this section presents overarching research needs from the perspectives of adaptation planning and engineering design, as well as specific research needs pertaining to individual asset types. The following section focuses on research needs relating to the overall process of conducting adaptation planning and engineering. The next section focuses on research related to the input values for the key variables in the design process. The final section proposes research topics for asset-specific adaptation engineering.

6.2 Research on the Approach to Adaptation Related Planning and Engineering

The *General Process for Transportation Facility Adaptation Assessments* (the *Process*) used in this study provided a useful construct for how planning and engineering design can be conducted taking into account the uncertainties associated with future design inputs. From the perspective of the overall approach, Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes, is one that provides the greatest change from traditional engineering design. In essence, this step states that in addition to historical data and the trends associated with such data, engineers should examine alternative possibilities for future conditions through the use of scenarios, and then determine the level of asset vulnerability under a range of scenarios. Depending on the resulting vulnerabilities, it may be appropriate to develop a design for each scenario.

The following three recommended research topics relate to the process of adaptation planning and engineering; that is, elements of the overall approach that structure how data for engineering analyses are developed and ultimately how the resulting information is used to determine priorities.

6.2.1 Use of Scenarios in Adaptation Planning and Engineering

One of the key areas for future research is continuing to examine alternative ways that climate change scenarios can be used in adaptation planning and engineering. For example, Figure 99 shows one perspective on how scenarios can be used - in this case leading to one alternative design that provides the most robust strategy in light of future environmental uncertainties. The consideration of scenarios is one of the major approaches being used by planners to account for uncertainties in future conditions or characteristics. As shown in the engineering case studies, the scenario approach used in this study was very influential in the case study results. The proposed research would look at different ways that scenarios could be used in adaptation planning and engineering. In addition, the research would examine the role of land use scenarios in identifying

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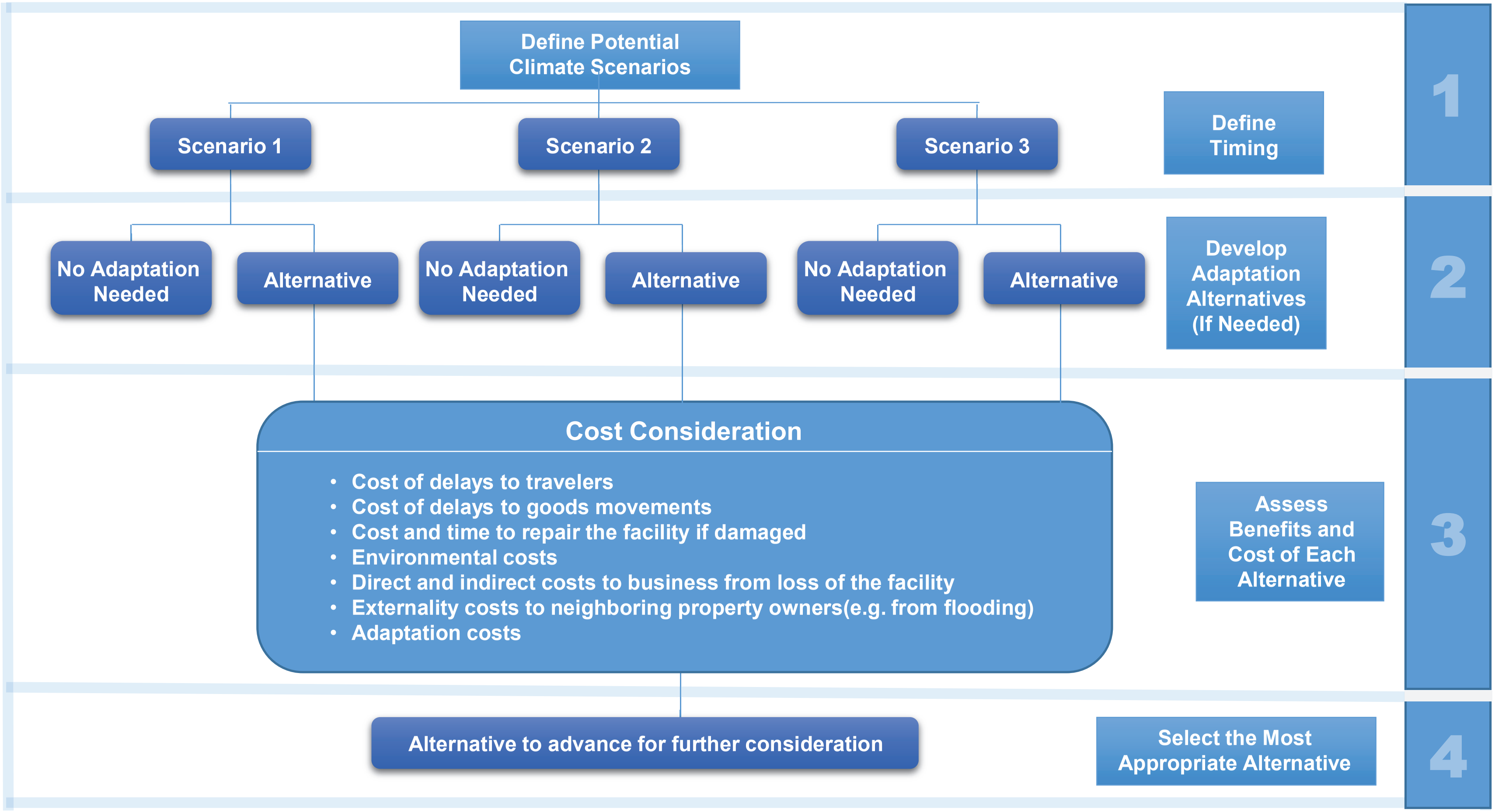
future climate change-related risks to a community (see next research topic). Although it may be important to look at different climate stressors simultaneously (such as sea level rise *plus* precipitation, which could have an additive impact on drainage), care must be taken when doing so. Projections for each climate variable were developed independently, and there is often no justification for assuming, for example, that a certain precipitation scenario would happen under the same "future" as a certain sea level rise scenario. This is not to discourage consideration of multi-stressor climate scenarios when managing risks to infrastructure. Indeed, all climate projections and scenarios are developed based on certain assumptions, and none are considered more/less likely to occur than others; developing future scenarios with multiple climate stressors is another form of scenario-planning, but doing so may increase the overall uncertainty regarding the scenarios. Additional research should look at ways to better evaluate simultaneous climate stressors without exaggerating a "worst case" scenario and without introducing unacceptable levels of uncertainty.

Figure 99: Use of Scenarios in Adaptation Planning and Engineering



6.2.2 Development of Future Surge Scenarios

As was noted in Section 4.4.4, the method for developing storm surge scenarios with respect to the return period event and wave modeling is an important area of research. Different approaches can be used based on the data and models that are available, the desires of local groups to link an event to local experience, and level of desired consistency with engineering practice. Research could examine the degree to which approaches differ in terms of level of impact, the relevance of the results to local decision making and the incremental benefit in terms of scenario output of using a more complex and sophisticated approach versus one that simplifies the process.

6.2.3 Consideration of Future Land Uses

Note that in the "cost considerations" element of Figure 99 that one category of costs is "externality costs to neighboring property owners." Many of the climate change-related vulnerability assessments in the U.S. have assumed current land use patterns, and have not included a consideration of future land use types or densities (with a notable exception being the Environmental Protection Agency's Integrated Climate and Land Use Scenario [ICLUS] initiative).[504] For a process that is examining a 50- to 80-year timeframe, assuming no change in land use patterns is unrealistic, especially when one needs to determine levels of criticality and risk for different types of assets in the transportation system. Another use for scenario analysis would thus be to consider land use scenarios that reflect possible changes to the community that should be considered in the analysis.

6.2.4 Incorporation of Adaptation Results into Decision-Making

The engineering case studies recommended adaptation strategies for individual transportation assets. Except in one case, the culvert case study, the economic analysis was not done to determine the overall cost effectiveness of the recommended strategy. No effort was made to compare the adaptation strategies among different assets to determine which ones would be better from the perspective of benefits and costs. And no effort was made to take the next step, which is to investigate how individual adaptation projects should be considered in the context of larger investment programs.

In particular, there is a disconnect between the timeframe for most metropolitan long-range transportation plans (20 to 25 years) and the 50 to 80-year timeframe associated with most adaptation planning.[505] Important questions relate to how the results from adaptation planning and engineering design efforts can be included in the transportation planning and programming process of typical metropolitan planning organizations (MPOs), states, and other investors. How does one prioritize adaptation projects in conjunction with capacity, safety, security, economic

[504] EPA, 2014
[505] A similar, more striking disconnect can occur in situations where federal funds are released after an extreme weather event. These funds may be released with the intention of quickly bringing a damaged transportation system back to its normal state of operation. These funds often have requirements that they be spent within a certain near-term timeframe, making it particularly difficult to undertake thoughtful analyses of climate risk.

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development and other types of projects? Where will the funding come from to pay for adaptation-related strategies? With limited resources, most state transportation agencies and MPOs may find it difficult to implement an adaptation-specific investment program. It will thus become important for planners and engineers to identify the co-benefits associated with adaptation strategies. What benefits will a reconstruction project have for safety, congestion mitigation as well as adaptation?

6.3 Research on Generating Input Values for Engineering Designs

One of the most important factors in determining engineered adaptations to threatened assets is the value of the input variables that guide engineering design. As noted in Section 5.3, future climatic conditions are likely to produce different values than what has been seen historically. How one determines such values is still a critical research question. The climate scenario approach used in this study provided values based on modeling results and on assumptions about the type and magnitude of climate-related stresses on transportation assets. As also noted in the previous section, this approach is new to engineering design, which has relied on design storms that are defined by historical record. Engineering designers have traditionally based decisions on probability of occurrence or exceedance of certain input variables and are comfortable with that approach. The probability of exceedance approach to input variables has a long and relatively-well understood history. In some cases, a site-specific evaluation based on benefit/cost ratios may be warranted, for example, when replacing a culvert that was put in place before an area was fully developed and now would represent a high economic loss if the culvert were to fail if replaced in kind. Developing tools that can simplify the analysis process would be useful.

6.3.1 Deriving Input Values for Design Variables

Given the importance of the values for design variables, research is needed on examining alternative methods for estimating such values. For example, the development of climate change intensity-duration-frequency (IDF) curves that reflect possible changing climatic conditions is recommended to aid in the translation of climate model outputs into inputs useful for engineering design. This is particularly important for some asset types, such as smaller culverts, where 24-hour projections may not be applicable; such design relies on IDF curves for which downscaled climate model data is not readily available.

Updating design flow equations based on more recent or projected climate data could be another way to incorporate changing climate data. However, more thought is needed about how to uniformly incorporate new climate data across all design activities.

6.3.2 Using Asset Management Systems as a Platform for Vulnerability Assessment

As was repeatedly found in every engineering case study, data on asset condition and performance was difficult to obtain and monitoring of supporting infrastructure was limited.

Infrastructure fails more frequently due to compromised structural integrity exacerbated by moderate climate events rather than by extreme conditions. This increased wear and tear on assets emphasizes the need for good asset management systems that proactively identify assets vulnerable to failure.

In addition, it was a challenge finding data on the latest geotechnical studies or structural integrity tests. Research is needed to illustrate how asset management systems can be used to monitor asset response to changes in climate and provide the data desired and needed for conducting adaptation engineering analysis. Moving Ahead for Progress in the 21st- Century (MAP-21) has placed greater emphasis on risk-based asset management and every state DOT is in the process of either developing or upgrading asset management systems to meet Federal requirements. Now is the time for the link between climate change and extreme weather-related asset considerations and evolving asset management systems to be examined closely.

6.4 Research on Asset-specific Needs

The following research topics resulted from the engineering work that was conducted as part of the case studies.

6.4.1 Culvert Vulnerability

Culverts are one of the most important components of any linear facility. The level of analysis conducted in the culvert case study for understanding the level of vulnerability was quite extensive and most likely beyond the time and resource constraints of most transportation agencies. There is thus a need to refine the culvert vulnerability analysis methods developed in this study, and also investigate new measures of culvert vulnerability to increased flows and other factors that could be applied more generally or as part of an asset management system. This topic could be expanded to look at failure modes for a range of possibly at-risk facilities.

6.4.2 Controlled Failure Approaches

The bridge case studies found that the bridge deck was vulnerable to each of the three surge scenarios tested. Design of a controlled failure superstructure was, in some cases, found to be a reasonable design option for low lying bridges in such environments. Research is needed to determine if other types of transportation assets can also be designed with breakaway components, such that the level of disruption to facility users would be minimized as the recovery process proceeds.

6.4.3 Embankment Breaching

The case studies that examined the impact of storm surge and wave action on embankments and abutment erosion found that the information most lacking for design purposes is the phenomena related to embankment breaching. Many studies have established estimates of flow rates and breach dimensions for earthen dams and levees, but not many have developed methods to predict

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the onset of embankment breaching or focus on highway embankments that are somewhat protected by pavement on top. This is an area of future research that would be needed in order to more accurately predict the impact of inflow and outflow from storm surge flooding on highway embankments.

6.4.4 Shipping Pier-related Research for Extreme Loads

Research and testing is necessary in order to establish a procedure for both load development and structural analysis of shipping piers that can be adopted universally for structures of the type examined in the case study with varying configurations. This research should culminate in a credible design guide that could act as a resource to shipping pier designers. The limited guidance that is currently available should continue to be vetted by comparing theoretical results with the loads and stresses on shipping piers that result from actual events.

6.4.5 Erosion Due to Backflows

Although engineering design today considers the potential of erosion due to water flows at embankments and other types of supporting structures, the potential for such erosion at underpasses (that funnel water flows during surge events) as water flows back to the coast deserves greater attention.

6.4.6 Abutment Scour

Abutment scour analysis procedures should be developed to allow for more accurate prediction and characterization of abutment scour in coastal areas. For example, with improved prediction methods and tools, structural design guidelines might focus on providing stable abutments without the need for outside protection schemes, such as riprap or bulkheads.

6.4.7 Temperature-related Design Parameters

The results of the pavement and rail case studies showed that under the "Hotter" narrative of future climate in Mobile, design had to move towards asphalt binders rated for higher temperatures and coarser aggregates. Rail track design practices as they relate to rail heat kinks do not consider the uncertainty relating to higher expected temperatures. For example, more research is needed on the appropriate value of rail neutral temperatures in the context of rail track design. Specifically with regard to rail design, the viability of using the Federal Railroad Administration's (FRA) rail weather system for rail engineering analysis should be subject to further research.

6.4.8 Guidance on Pavement Design

One of the lessons learned from the pavement design case study is that additional guidance is needed with respect to how potential changes in climate will affect pavement performance, and thus the design process. Although not a research topic per se, the need to develop such a guide

and to modify existing pavement design software to account for projected temperature conditions is an important next step that results from the work conducted in this study.

6.4.9 Weighing Costs versus Benefits of Adaptation in Light of Uncertainty

The analyses described in this report relied upon the development of certain future climate scenarios. There is inherent uncertainty associated with these scenarios, and it is not possible to make a determination as to which scenarios are more likely to occur. As discussed earlier, the choice of scenario(s) can have significant influence over the outcome of these analyses, and looking across a range of scenarios could yield a significant range of uncertainty regarding possible impacts on an asset.

This uncertainty raises challenges when evaluating costs and benefits. However, future research could evaluate not just the benefits and costs of implementing a specific adaptation measure, but it could also investigate how to determine the point at which marginal costs of adaptation get significantly larger or smaller. If more modest improvements are relatively inexpensive, it may make sense to focus on making those improvements rather trying to justify more extensive expenditures that yield only marginal benefits. Conversely, some adaptation measures may have significant upfront costs, and additional improvements result in small marginal costs. In this situation, it would be useful to understand whether the benefits associated with the minimal level of improvement outweigh the initial costs, or whether it is important to be able to justify more extensive improvements.

6.4.10 Additional Research on Prioritizing Assets to Undergo Analyses

The analyses presented in this document demonstrate potential methodologies for evaluating climate change impacts and adaptation strategies at the project level. To date, there have been only limited efforts to develop detailed methodologies appropriate for the project level; most climate change vulnerability assessments and adaptation evaluations have either been at a broader level, or were very narrowly focused on a specific asset without regard to replicability of the methodologies to similar assets elsewhere.

However, conducting these analyses are resource-intensive, and it is unrealistic to think that most transportation managers would be able to conduct these analyses for all assets under their purview. In fact, attempts to do so could result in wasted time and money if efforts to narrow down the list were not made first. To narrow the list of assets for this project, the project team conducted a criticality assessment and vulnerability screen earlier in this project, to identify which assets were both highly critical and potentially vulnerable. However, for many asset types, there were still a number of assets that were considered highly critical and vulnerable. It would be useful to explore other approaches for further narrowing down the list of potential assets to analyze. Such approaches could even be employed if no criticality or vulnerability assessment were conducted.

Prioritization approaches could consider the remaining useful lifetime of assets against the timeframe of climate changes, the potential costs of damages associated with impaired use of the asset or repair costs, or more specific indicators of vulnerabilities that are geared toward very particular asset types.

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Hampton Roads
Climate Impact Quantification Initiative

Baseline Assessment of the Transportation Assets & Overview of Economic Analyses Useful in Quantifying Impacts

September 13, 2016

U.S. Department of Transportation
Research and Innovative Technology Administration
John A. Volpe National Transportation Systems Center
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Notice

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13. ABSTRACT (Maximum 200 words)

The Hampton Roads Climate Impact Quantification Initiative (HRCIQI) is a multi-part study sponsored by the U.S. Department of Transportation (DOT) Climate Change Center with the goals that include developing a cost tool that provides methods for voluntary grantee consideration of financial impacts in infrastructure planning due to climate change and severe weather. This Baseline Study, conducted in collaboration with several DOT modes, and based on extensive consultation with regional governmental, military and industry stakeholders, summarizes available data, methodologies, and tools to inform a robust analysis of the economic impacts of climate change and severe weather-related disruptions on the region's transportation infrastructure. DOT chose to study the Hampton Roads region based on its unique attributes, including its: extreme vulnerability to sea level rise impacts, that is beginning to threaten transportation system and military operations; strategic significance as home to the nation's largest concentration of federal facilities, including the world's largest naval station; and the partnership opportunities afforded through the Intergovernmental Pilot Program and its partner's deep expertise in analyzing and addressing these impacts. DOT is intending to conduct follow-on work building on this Baseline Study.

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EXECUTIVE SUMMARY

The Department of Transportation (DOT) Climate Impact Quantification Initiative study (DOT Quantification Initiative or "Initiative") summarizes available data, methodologies, and tools to inform a robust analysis of the economic impacts of climate change and severe weather-related disruptions on the Hampton Roads (HR) region's transportation infrastructure. Based on extensive stakeholder involvement, this assessment focuses both on the HR region and the City of Norfolk. First, the effort was scoped and established in conjunction with, and supported a broader effort by the HR Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (IPP HR Pilot) convened by Old Dominion University (ODU), Norfolk, VA. Second, the study will support ongoing efforts by DOT to collaborate with federal, state, and local transportation officials, including industry, to adapt to future impacts in the HR region due to climate change and severe weather.

This study also addresses the interdependency of the transportation network with the broader regional economy and related critical assets and functions, including military preparedness, emergency response and utilities.[1] The HR region, home to the nation's largest concentration of federal facilities, including the world's largest naval station, Naval Station Norfolk, is highly vulnerable to sea level rise, which is beginning to threaten the multi-modal transportation infrastructure and military operations. While not all functions and assets can be quantified, their value is significant to the public, governments and industry.

The established method for measuring risks uses the combination of the probability of the event occurring and the associated consequence of the event. Understanding system vulnerabilities to climate change requires assessing climate-related threats and identifying infrastructure vulnerabilities to those threats. Adaptive measures for reducing identified vulnerabilities can then be considered. Understanding the costs of disruption to the economy (monetized or not) is an important consideration for evaluating adaptive measures. For the quantification of the costs of damaged transportation assets and loss of use of transportation service, the same process can be applied.

This study complements and builds upon other DOT assessments, including the Gulf Coast Studies. Such studies have traditionally focused on the vulnerability of transportation assets to flooding, sea level rise, and storm surge, though some DOT FHWA pilots have augmented such assessments with economic analyses comparing a "do-nothing" scenario against possible

[1] The HR pilot, convened by Old Dominion University, is unrelated to the 2012 VDOT HR Pilot funded by the Federal Highway Administration.

adaptive strategies. A few pilots also considered indirect social, environmental, and economic impacts to varying degrees. For example, the DOT Hillsborough pilot estimated economic losses associated with business and truck delays, lost trips, and vehicle operating costs over a five-day period after a storm event based on the disruption of specific vulnerable transportation facilities. However, these analyses, while useful to considering cost-effective strategies for a given asset, have not to date considered the full range of economic impacts, such as expansive indirect costs, due to transportation disruption.

Within the HR region, there have been a number of analyses considering the potential climate vulnerabilities within the transportation system. These analyses largely focus on flooding impacts related to sea level rise, heavy precipitation events, and storm surge. In addition, a few studies have further considered the economic consequences of storm events. However, similar to the DOT studies summarized above to date, such studies have not considered the "full cost" of future climate-driven storm events that includes both the direct transportation costs (e.g., damaged or destroyed assets) as well as the indirect economic costs as a consequence of loss of transportation services. This report fills an important gap by accounting for indirect losses due to business interruption and loss of earnings, loss of insurance protection due to frequency of disruption, and amplified effects of poverty. This report, through an extensive consultative process that leveraged a wealth of local and regional expertise, assesses the available building blocks and methodologies to conduct such a comprehensive analysis on the HR region.

The structure of this report includes: (1) a summary of the current state of knowledge to inform an analysis for quantifying economic costs of climate change; (2) descriptions of economic methodologies currently in-use by USDOT and resources available for assessing assets and monetizing impacts; and (3) a roadmap of possible steps for conducting a comprehensive economic quantification in HR.

SUMMARY OF FINDINGS

Part 1 considers the available data and information for Hampton Roads that are necessary for this economic analysis. Transportation Asset Inventory and Data for Economic Analysis

- Overall, there is significant data for bridges and roads, followed by sea ports/waterways, and airports. There is less information for tunnels, railroads and pipelines. However, the National Tunnel Inventory (NTI) will in the coming years provide additional information describing tunnel inventory, use, and condition. Valuation information for tunnels, bridges, and roads includes depreciated values and replacement costs; while valuation information for sea ports/waterways and airports only considers revenue (see Figure SF-1; see Section 1-1).
- Light Detection and Ranging (LiDAR) data collected from 2011 to 2014 provides elevation data useful for understanding asset exposure to flooding. GIS shapefiles have been developed for roadways and elevated roadway structures (e.g., bridges). Additional effort would be required for similar processing of railroads.
- There is minimal information concerning asset condition (see Section 1-1).
- There is some valuation information available; however, much of it is simply the past project cost of constructing the asset or revenues associated with operations (e.g., airports) (see Section 1-1).

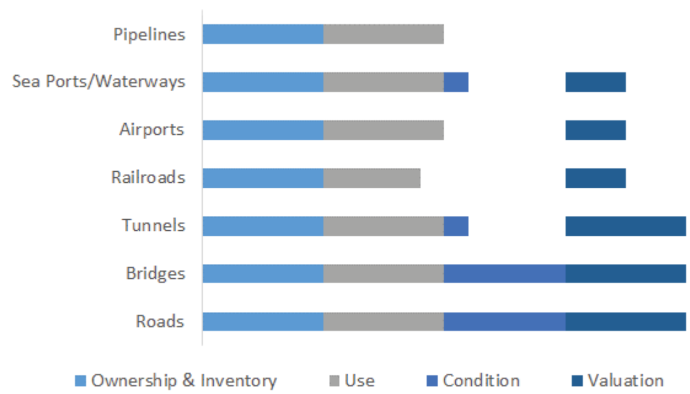


Figure SF-1. Qualitative description of data identified by transportation asset type and described in this report

Indirect Consequences

- There are significant economic consequences for transportation failure, reduced services, and/or implementing adaptive strategies. Data considering these indirect impacts include business interruption and costly consequences for utility services/assets. In addition, there are concerns of social vulnerabilities where certain populations may be more affected. Data are available that identify key economic sectors in the region, critical infrastructure facilities, and indices describing social vulnerabilities (See Section 1-2).

Exposure

- HR is exposed to a number of weather- and climate-related events including sea level rise, storm surge, heat events, and heavy precipitation. All of these stressors are projected to increase to some degree in the coming decades (see Section 1-3).
- Two studies in the HR region have recently been completed that identify transportation asset exposure to sea level rise and storm surge, and consider broader system vulnerabilities (see Section 1-3).

Impact Analysis

- There was no available information or databases describing sensitivities to extreme weather events. Because of this, this study: (i) identified historic storms that caused significant damage and considered associated impacts with an emphasis on transportation assets; (ii) reviewed and presented past impact studies for HR. Hurricanes/tropical storms and nor'easters were the storm events that caused the greatest storm-induced damages (see Section 1-4).
- Three studies considering sea level rise and storm surge identified sector vulnerabilities including transportation within HR and, in some cases, provided monetized values of the impacts (see Section 1-4).

Adaption

- There are a number of adaptation efforts that have been evaluated or are underway in HR. Though many of these efforts are not specific to transportation, this information provides insights of proposed projects that may affect transportation impacts and a reference for related project costs. This information is helpful in understanding potential costs if such strategies were considered in an economic analysis in areas where vulnerabilities may be affected/introduced/alleviated by the adaptation project (see Section 1-5).

Quantifying Cost Burdens

- There are a number of challenges regarding quantifying the cumulative costs of such low-impact/high probability stressors such as recurrent flooding. For high-impact/low probability events, there is concern the costs may fall largely on the taxpayer (see Section 1-6).

Part 2 provides an economic primer illustrating the current methodologies used by the Department of Transportation (DOT), Federal Highway Administration (FHWA). Many of these methodologies (e.g., Life-Cycle Cost Analysis (LCCA), Benefit Cost Analysis (BCA), etc.) do not consider the possible indirect impacts as discussed above. This section considers ways to incorporate such costs. In addition, available tools are considered for their usefulness. Overall, there is not one tool that has been developed that can be used "as is" for this analysis.

Part 3 crosswalks the findings of Part 1 and Part 2 to provide a roadmap of possible steps for conducting an economic quantification in HR.

INTRODUCTION

> *The Hampton Roads area in Virginia is experiencing the highest rates of sea-level rise along the entire U.S. East Coast. The area is also second only to New Orleans, LA, as the largest population center at risk from sea-level rise in the country.*
>
> Source: WRI (2014).

The Hampton Roads (HR) region, highly dense in transportation infrastructure, is one of the most vulnerable regions to flooding in the nation. Since 1997, extreme weather events have caused havoc across the HR region, causing more than $800M dollars in property damage.[2] The greatest monetized property damage was caused by hurricanes and flood events. These events have also significantly affected the transportation and energy sectors. In addition, recurrent "nuisance" flooding has increased dramatically in recent years and have caused large disruptions to regional transportation networks.[3] There is growing concern that given changes in climate and land-use, the impacts of these events and their impacts will increase. Of particular concern to the Hampton Roads region are sea level rise, storm surge, and heavy precipitation. Projections suggest these climate-related stressors will increase in frequency, magnitude, and/or duration. This report lays out the building blocks of the data and resources available for conducting an economic quantification of the climate-related impacts, such as disruption, on HR's transportation system.

> **DOT Terminology**
>
> **Resilience**: The ability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.
>
> **Exposure** refers to whether the asset or system is located in an area experiencing direct impacts of climate change.
>
> **Sensitivity** refers to how the asset or system fares when exposed to an impact.
>
> **Adaptive capacity** refers to the system's ability to adjust to cope with existing climate variability or future climate impacts.
>
> **Vulnerability:** In the transportation context, it is a function of a transportation system's exposure to climate effects, sensitivity to climate effects, and adaptive capacity.
>
> Source: USDOT FHWA (2012a).

DOT has recently contributed to studies in HR regarding the impact of climate change and extreme weather through conducting a pilot assessment (2011).[4] In addition, from 2014-2016, a representative from DOT's Climate Change Center participated in the HR Intergovernmental Planning Pilot (IPP) convened by Old Dominion University as member of the Working Groups on Infrastructure and Economic Impacts WG. During the IPP process, which was attended by transportation and planning experts and local governments (see text box, below), DOT recommended creating a tool to quantify transportation impacts, and the idea was endorsed. Specifically, in its 2015 report, the IPP stated: "There are

[2] Based on our analysis using the NOAA Storm Event Database.
[3] Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (2015).
[4] HRTPO (2013b).

significant data gaps that need to be addressed with respect to Economic Modeling in Phase II [of the Pilot] and beyond. For instance, the IWG has concluded that any planning activities taken to address infrastructure need to address the cost and benefits of proposed actions to aid in decision-making."[5] In May 2016, DOT helped organize, with the HR IPP, and participated in a workshop on economic quantification attended by over 50 governmental, academic, and industry parties where DOT presented a draft of this report and sought comment. During its presentation on the draft Quantification Report, DOT explained that its objective, in concert with HR stakeholders, was to develop a cost tool that could, among other things, provide methods for voluntary grantee consideration of financial impacts in planning due to climate change and severe weather.[6] DOT continued to work with the IPP and others to further refine this report through formal and informal consultation, as summarized in the text box, titled Outreach and Collaboration in Hampton Roads: The "Whole of Government" Approach.

A number of entities were involved in HR's Intergovernmental Planning Pilot (see textbox below). The IPP has adopted an overall framework for assessing the risk/vulnerability of transportation assets to climate change and extreme weather that is used throughout the planning community:

- Develop an inventory of the transportation network and assets;
- Identify current and future climate hazards and stressors;
- Characterize risks/vulnerabilities that threaten assets and system functions;
- Identify initial adaptation strategies;
- Integrate strategies into system operations and implementation planning processes;
- Monitor, assess performance, and revise risk/vulnerability scenarios and adaptation strategies.

These steps closely follow the Department of Transportation's (DOT) Federal Highway Administration (FHWA) Framework for Climate Change & Extreme Weather Vulnerability Assessment (see Figure 1). This framework encapsulates much of the common elements followed by many agencies when conducting a risk/vulnerability assessment. These steps can be applied at various scales within the region's transportation system (e.g., across all nodes of transport or drilled down to a specific asset class within the study region). There are a few economic entry points into this framework, specifically including: (1) considering asset criticality; (2) considering the economic consequences of climate-related events; and/or (3) the implementation of adaptation strategies.

[5] Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (2015).
[6] Old Dominion University et al. (2016).

Outreach and Collaboration in Hampton Roads:
The "Whole of Government" Approach

DOT's approach to scoping the project involved intensive consultations with participants in the Hampton Roads Intergovernmental Pilot Project (IPP) over a two-year period. The DOT supported the Infrastructure Planning Working Group and Economic Impact Advisory Committee through monthly in-person meetings. It worked with HR planning agencies—Hampton Roads Planning District Commission (HRPDC), Hampton Roads Transportation Planning Organization (HRTPO), Virginia DOT, and municipal and state government entities. The process, convened by Old Dominion University, has been dubbed a "whole of government" approach.

DOT also presented at the following forums:

Alasdair Cain, Co-Chair, DOT Climate Change Center, Collaborations and Community Resilience Conference, ODU, Federal Panel with Cap. Pat Rios, Comm Officer, Naval Facilities, Middle Atlantic, U.S. Navy Rebecca Patton, Climate Change Adaptation Integration, U.S. DOD (December 10, 2015).

Alan Strasser, Steering Committee, DOT Climate Change Center, Bahar Barami, Economist, Volpe Center, The Economic Impacts of Sea-Level Rise in Hampton Roads: An Appraisal of the Projects Underway. Old Dominion University, Virginia Modeling and Simulation Center, Suffolk, VA (May 18, 2016).
In addition, DOT participated in additional stakeholder discussions to solicit information and feedback:

Alan Strasser, Project Coordinator, DOT Climate Change Center, Rawlings Miller, Climate Resilience Specialist, Volpe Center, Bahar Barami, Economist, Volpe Center, David Arthur, Branch Chief, Volpe Center, Kristin Lewis, Environmental Scientist, Volpe Center, Alasdair Cain, Co-Chair, DOT Climate Change Center, Shawn Johnson, DOT Climate Change Center, Meeting at Hampton Roads Transportation Planning Organization and Hampton Roads Planning District Commission, Chesapeake, VA (July 7, 2016).

Alan Strasser, Project Coordinator, DOT Climate Change Center, Rawlings Miller, Climate Resilience Specialist, Volpe Center, David Arthur, Branch Chief, Volpe Center, presented Hampton Roads Climate Impact Quantification Initiative. Transportation Technical Advisory Committee (TTAC), Chesapeake, VA (September 7, 2016).

Alan Strasser, Project Coordinator, DOT Climate Change Center, Rawlings Miller, Climate Resilience Specialist, Volpe Center, David Arthur, Branch Chief, Volpe Center, presented Hampton Roads Climate Impact Quantification Initiative. Virginia Maritime Association, Norfolk, VA (September 7, 2016).

[1]A partial list of stakeholders involved in the HR Pilot include: Hampton Roads Transportation Planning Organization; Virginia DOT, Hampton Roads Planning District Commission, City of Norfolk, City of Virginia Beach, City of Newport News, and the U.S. Navy. For more information on the Pilot, including its Phase I report of 2015, see: http://www.centerforsealevelrise.org/research-resources/pilot-project-resources.

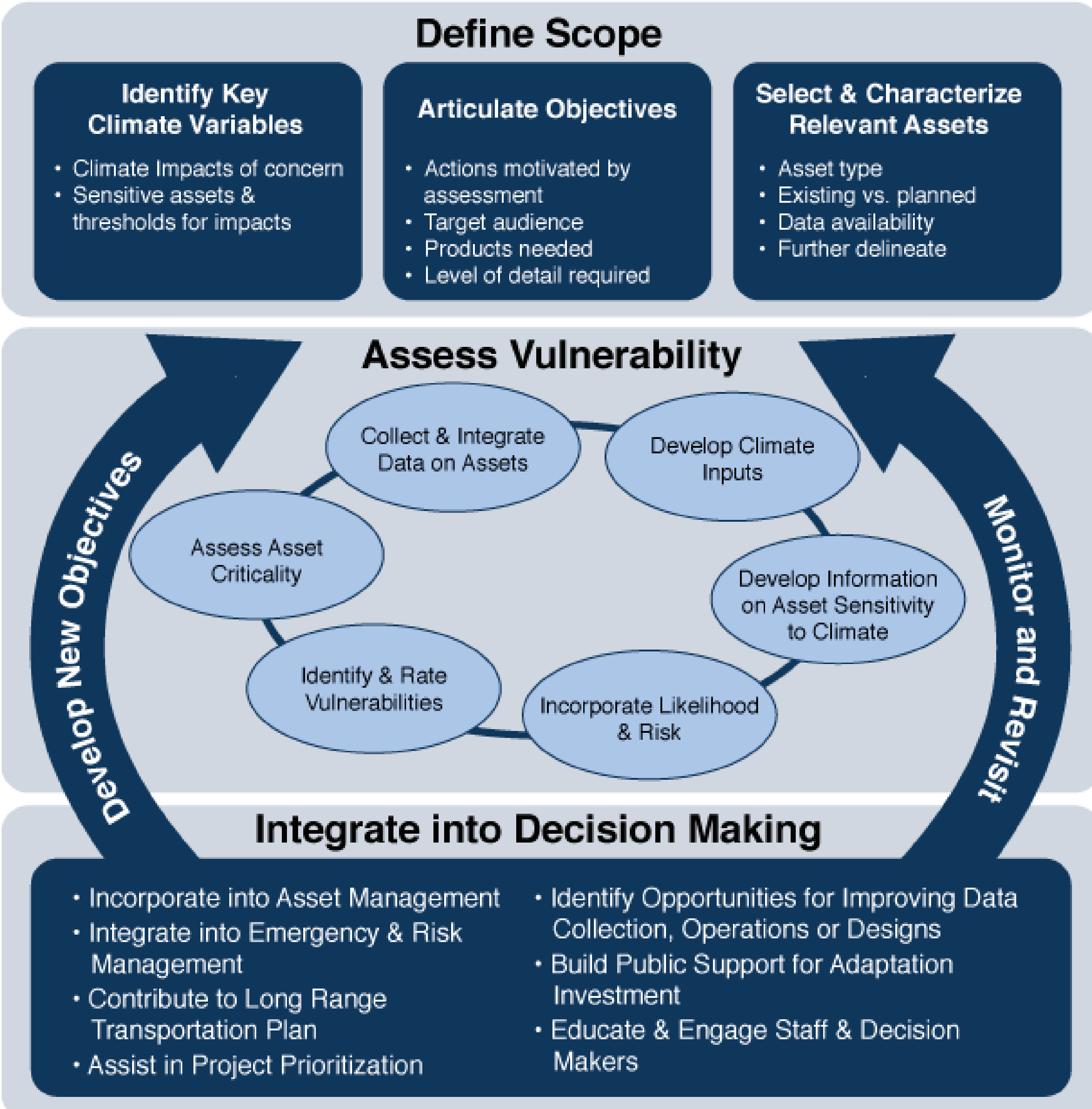


Figure 1. DOT FHWA Framework for Climate Change & Extreme Weather Vulnerability Assessment (Source: USDOT FHWA (2012a))

Zooming down to the facility-specific level, Department of Transportation (DOT) Federal Highway Administration (FHWA) developed an 11-Step Process for conducting a facility-specific[7] assessment and developing adaptation strategies.[8] This approach can be implemented, e.g., once a critical asset has been identified as vulnerable, following the steps as provided in the textbox entitled, *The Process*. Step 8 outlines a methodology for conducting an economic analysis which evaluates how benefits of implementing an

[7] Examples include pavement, bridge, and flood protection.
[8] USDOT (2014a).

adaptation strategy (i.e., costs avoided) compared to the incremental costs under each possible future climate scenario.

The Process

1. Describe the site context;
2. Describe the existing/proposed facility;
3. Identify climate stressors that may have an impact infrastructure components;
4. Decide on climate scenarios and determine the magnitude of changes;
5. Assess performance of the existing/proposed facility;
6. Identify adaptation option(s);
7. Assess performance of the adaptation options;
8. Conduct an economic analysis;
9. Evaluate additional decision-making considerations;
10. Select a course of action;
11. Plan and conduct ongoing activities.

Source: USDOT (2014a).

However, what is missing from both the framework and facility-level approach described above is a means to consider the overarching economic consequences associated with transportation loss that affect the region both during and after the storm event and contribute to comparing the economic costs and benefits of possible adaptive measures. By including such considerations, this study will create pathways within the DOT FHWA Framework for integrating economic consequences into "smart" decision making; i.e., without including these potentially larger economic impacts, the decisions reached are based on a somewhat myopic analysis. For example, we need to quantify climate-related losses associated with the costs of social vulnerabilities to capture the extent of direct and indirect losses that arise from poverty, lack of transportation access, business interruption costs not captured as direct property losses, and the difficulty of assigning ownership rights to damaged property to allocate the responsibility for paying for the costs. Underscoring the sharp contrast between direct and total costs of a climate-related incident is a recent study by Sandia National Laboratories that estimated the potential range of "direct" economic losses from a 4-day flooding/SLR in Norfolk to range between \$27M to \$57M (depending on the SLR severity scenario).[9] However, the study found that direct losses accounted for only 38 percent of the total costs. When "indirect" costs that accounted for the remaining 62 percent of the total damage costs were added, Norfolk's total losses from a 4-day business interruption costs would escalate to between \$70M and \$145M.

This report surveys available information, data, and resources that may inform such an overarching economic analysis. The report is divided into three parts:

- **Part 1: Baseline Assessment**: Describes the available data and information useful for conducting a climate-related economic analysis.
- **Part 2: Overview of Economic Methodologies and Resources for Assessing Transportation Vulnerabilities and Quantifying Economic Impacts Related to Climate Change**: Provides a primer of economic methodologies useful to consider for this work along with available vulnerability and economic tools and resources.

[9] Sandia National Laboratories (2013).

- **Part 3: Conducting an Economic Quantification Study in Hampton Roads**: Presents a roadmap for a regional economic analysis based on the findings of Part 1 and Part 2.

METHODOLOGY

This analysis incorporates best available data—including Federal databases and publicly available reports and research findings—for developing a high-level initial baseline inventory of HR transportation assets at risk from climate change disruption (see Table 1). In addition, this analysis includes economic impact assessment tools and methodologies available for quantification of the economic costs of climate change. Unless otherwise noted, the dollar values are presented as nominal values as provided by the cited source (i.e., not adjusted to 2016 values). Many other public and academic studies and data sources have also been consulted, and stakeholder contributions were invaluable to this analysis. Appendices B and C provide the study references and an inventory of data sources consulted for this report. This information was collected by conducting a targeted literature search and through stakeholder participation. Interviews, conferences, and other forms of communications were conducted with Hampton Roads Transportation Planning Organization (HRTPO), Hampton Roads Planning District Commission (HRPDC), DOT FHWA Virginia Division, Virginia Department of Transportation (VDOT), Old Dominion University (ODU), United States Army Corps of Engineers (USACE), Virginia Maritime Association, among others. In addition, DOT held a spring workshop to present and discuss ongoing and upcoming climate-related economic analysis in HR.

Table 1. Summary of the data/resources and providers of reports used in this analysis

DATA / RESOURCES	REPORTS PREPARED BY
• FEMA HAZUS-MH • NATIONAL ATLAS DATABASE • NATIONAL BRIDGE INVENTORY (NBI) • NOAA NATIONAL CLIMATE DATA CENTER (NCDC) • UNIVERSITY OF SOUTH CAROLINA SHELDUS	• Hampton Roads Partnership • Hampton Roads Planning District Commission (HRPDC) • Hampton Roads Transportation Planning Organization (HRTPO) • Old Dominion University (ODU) • Sandia National Laboratories • US Department of Transportation (USDOT) • United States Army Corps of Engineers (USACE) • Virginia Department Of Transportation (VDOT) • Virginia Institute of Marine Science (VIMS)

STUDY AREA

This study adopted the Hampton Roads District Commission's definition of HR.[10] The HR[11] region, is spread over 16 jurisdictions, including 10 cities and 6 counties. The HR region is a subset of the larger Virginia Beach–Norfolk–Newport News Metropolitan Statistical Area (MSA); (1.64M population), as well as the VA-NC Combined Statistical Area that includes four additional counties in North Carolina, raising the total regional population to over 1.8 million residents.[12] HR cities include: Chesapeake, Franklin, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Suffolk, Virginia Beach, and Williamsburg. The six counties in HR include: Gloucester County, Isle of Wight County[13], James City County, Southampton County, Surry County, and York County. Unless otherwise specified, most data citations for this report relate to the City of Norfolk or the entire 16-jurisdiction HR. The table below shows the different geographic definitions of Hampton Roads, including the definition adopted in this report.

Table 2. Cities and counties located in HR as defined for the report and other regional definitions presented in this report

COUNTY/CITY NAME	HR AS DEFINED IN THIS REPORT	HRPDC DEFINITION OF HR	HRTPO DEFINITION OF HR	MSA*
CURRITCUK COUNTY, NC				X
GATES COUNTY, NC				X
GLOUCESTER COUNTY, VA	X	X	X	X
ISLE OF WIGHT COUNTY, VA	X	X	X	X
JAMES CITY COUNTY, VA	X	X	X	X
MATTHEWS COUNTY, VA				X
SOUTHAMPTON COUNTY, VA	X	X		
SURRY COUNTY, VA	X	X		
YORK COUNTY, VA	X	X	X	X
CHESAPEAKE, VA	X	X	X	X
FRANKLIN, VA	X	X		
HAMPTON, VA	X	X	X	X
NEWPORT NEWS, VA	X	X	X	X
NORFOLK, VA	X	X	X	X
POQUOSON, VA	X	X	X	X
PORTSMOUTH, VA	X	X	X	X
SUFFOLK, VA	X	X	X	X
VIRGINIA BEACH, VA	X	X	X	X
WILLIAMSBURG, VA	X	X	X	X

* Norfolk-Virginia-Beach-Newport News MSA

[10] HRPDC (2016).
[11] The term Hampton Roads, while connoting the broader Hampton Roads region, actually refers to a body of water called Hampton Roads, is one of the world's largest natural harbors. It incorporates the mouths of the Elizabeth River, Nansemond River, and James River with several smaller rivers and empties into the Chesapeake Bay near its opening to the Atlantic Ocean.
[12] "Metropolitan and Micropolitan Statistical Areas." See: http://www.census.gov/population/metro.
[13] Includes the Town of Smithfield.

This report presents the information at two-scales: (1) HR region as a whole and (2) Norfolk (depending on the context and availability of disaggregated data). In some instances, when the asset dataset being analyzed for this report required significant effort to evaluate, the analysis was curtailed to just the City of Norfolk to provide an example of its usefulness. Norfolk is used as an example because at the onset of the development of this report, the HR Pilot requested that we consider the Pretty Lake neighborhood as a pilot location for later work because of the existing and potentially worsening vulnerabilities to SLR/storm surge. The Pretty Lake neighborhood transects Norfolk and Virginia Beach (see Figure 2).

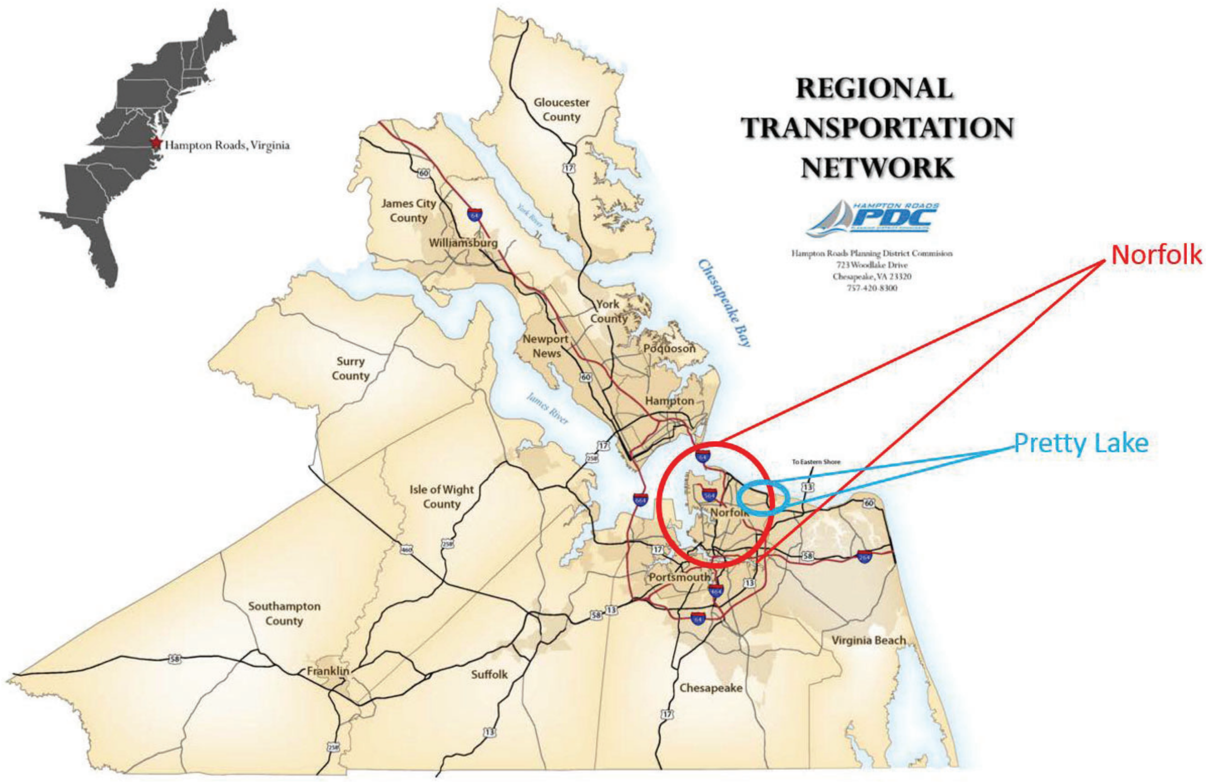


Figure 2. Hampton Roads, Norfolk, and Pretty Lake (Source: HRPDC Maps and GIS)

PART 1 – BASELINE ASSESSMENT

Estimating the economic impacts of climate change involves: estimating the likelihood of disruptive climate-related events; identifying the direct and indirect components of the costs; and crafting strategies that run the gamut from engineered protective measures, to accommodation strategies, to ultimate retreat. This section outlines available data and information to inform:

- Direct economic costs related to transportation loss during an event and asset vulnerabilities when considering asset sensitivities to a future event (Section 1-1);
- Associated indirect economic costs in response to loss of transportation services (Section 1-2);
- Understanding current and future asset exposure to events and two studies that identify transportation asset exposure to sea level rise (SLR)/storm surge (Section 1-3);
- Understanding disruptions during past events and recent studies that quantify climate-related impacts (Section 1-4);
- Costs associated with current or evaluated adaptive measures to curtail event-driven disruptions (Section 1-5);
- Challenges when quantifying the economic costs associated with low-risk/high probability events and the public burden of high-risk/low probability events (Section 1-6).

Each topic is discussed in detail below.

1-1 MULTIMODAL TRANSPORTATION NETWORK DATA

> *Hampton Roads is often described by its leaders as "the most infrastructure dependent-place on the East Coast."*
>
> Remarks by VA Transportation Secretary Aubrey Layne, May 2015; Congressman Randy Forbes (R-VA 4th District), March 2016, and; Norfolk Mayor Paul D. Fraim, February 2012.

This section provides an overview of the HR transportation network by asset- or service-type, with specific focus on HR and Norfolk area, depending on data availability.[14] A sizeable transportation network is located within HR including the Norfolk area, demonstrating the diversity of assets (see Figure 3). The following information is provided with gaps noted: inventory, use, condition, and valuation information (in some instances, revenue information is provided under the valuation category):

- Inventory: Summarizes available information regarding location, ownership, and quantity. GIS data availability is also noted. This is useful when considering criticality and exposure of assets.
- Use: Describes the frequency and type of users served by the asset-type. This is important for understanding criticality of assets and potential implications to the region if service is lost.
- Condition: Describes the condition of the assets. This is useful for understanding the remaining lifetime of the existing asset, the potential need for reconstruction (e.g., funding opportunities

[14] The Pretty Lake neighborhood is not specifically discussed in this section because the databases and information sources found and/or recommended did not disaggregate assets at the neighborhood scale.

particularly if a strategy could be considered as "no regrets")[15], and the possibility of enhanced sensitivities to exposure due to poor conditions.

- Valuation information: Provides data on estimating the construction and valuation costs of an asset and, in some cases, provides revenue information. This is useful in considering direct costs associated with a potential loss of asset.

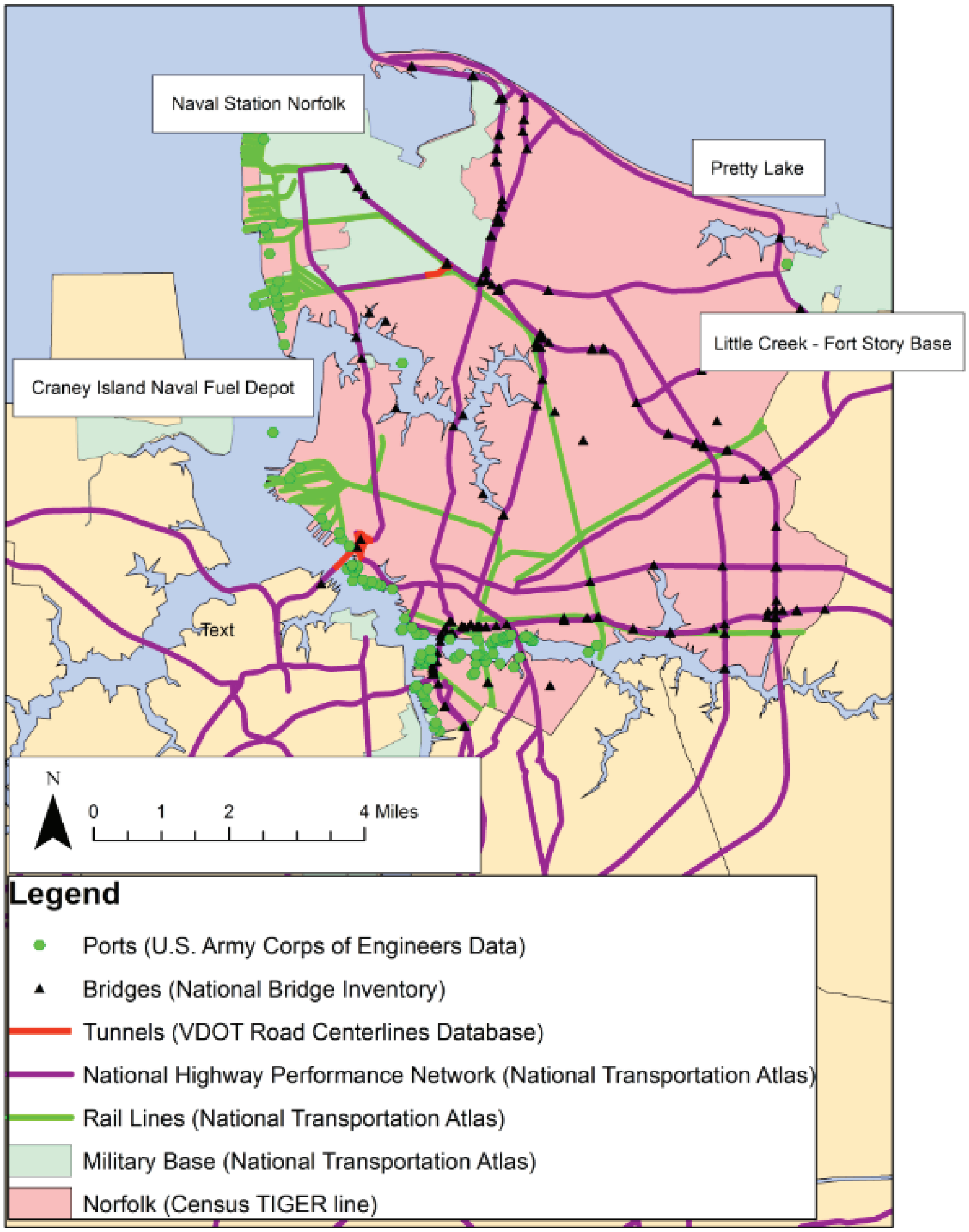


Figure 3. Norfolk highways, bridges, ports, and rail lines (Source: National Transportation Atlas Database (NTAD))

[15] A "no regrets" strategy is one that would be considered regardless of whether extreme events are amplified by climate change.

For this section's discussion on service-types, the operations and use are discussed.

HRTPO Prioritization Tool and Scoring Criteria: Economic Vitality

HRTPO developed a tool for prioritizing possible transportation projects. This tool scores a project based on project utility, project viability, and economic vitality. The criteria used in scoring a project's economic vitality may be useful when considering economic metrics in a regional economic quantification study. These criteria have already been vetted by the region, are familiar to transportation stakeholders, and represent economic drivers in the region. For example, the criteria include whether the transportation facility increases access to the port facilities, tourist destinations, defense installations, and high density employment areas. See Appendix D for additional details.

Source: Adapted from communication with representatives from HRTPO

1-1-1 Asset Categories

Roads

Ownership & Inventory. There are a total of 11,767 miles of roads within HR including 1,094 miles of roads within Norfolk. These roadways include a diversity of centerline data types from interstate highways to base roads on military installations (see Table 3).

Table 3. Roadway centerline miles in Hampton Roads by roadway type (Sources: based on data from HRPDC (2012); Norfolk OpenGIS; per communication with HRTPO representatives)

ROADWAY	OWNERSHIP	FUNDING	HR TOTAL (CENTERLINE MILES)	NORFOLK TOTAL (CENTERLINE MILES)
INTERSTATE	VDOT	Eligible for Federal funding	250	102
PRIMARY	VDOT, VA cities	Eligible for Federal funding	1,460	98
SECONDARY	VDOT, VA cities	Eligible for State and Federal funding	2,216	169
LOCAL OR PRIVATE	VDOT, VA Cities, Federal	Eligible for State funding*	7,841	643
BASE ROADS (MILITARY)	Military		NA	82
TOTAL ROAD-MILES			**11,767**	**1,094**

**Private roads do not receive state funding. To be eligible for state funding, a road must be on a state-maintained road network (this may include local roads in subdivisions). Urban public roads are eligible for state and federal funding.*

HRPTO has produced a GIS shapefile that provides roadway location and road bed elevation useful for identifying roadways that could be submerged under various inundation scenarios.[16] This GIS shapefile was developed based on elevations constructed from Light Detection and Ranging (LiDAR) data and HRPTO GIS road layers.[17] The GIS shapefile is very useful, though there are a few limitations: (1) additional analysis is required to accurately portray roadways constructed at higher elevations, and (2) the centerline of roadways was used to represent the roadways, thereby not capturing roadways that may be partially flooded.

Use. Roads play a critical role in the transport of employees to/from work. Daily vehicle miles traveled (DVMT) in HR was estimated at about 40M in 2011.[18] Spatially, the work-related commuter patterns are complicated, with significant travel across much of the region (see Figure 4).[19] The largest subset of travelers appear to be traveling within the southeastern portion of the region, particularly for travel to/from the Suffolk, Chesapeake, Norfolk, and Virginia Beach cities (thickness of the arrows provide relative measure of the number of travelers compared to other routes).

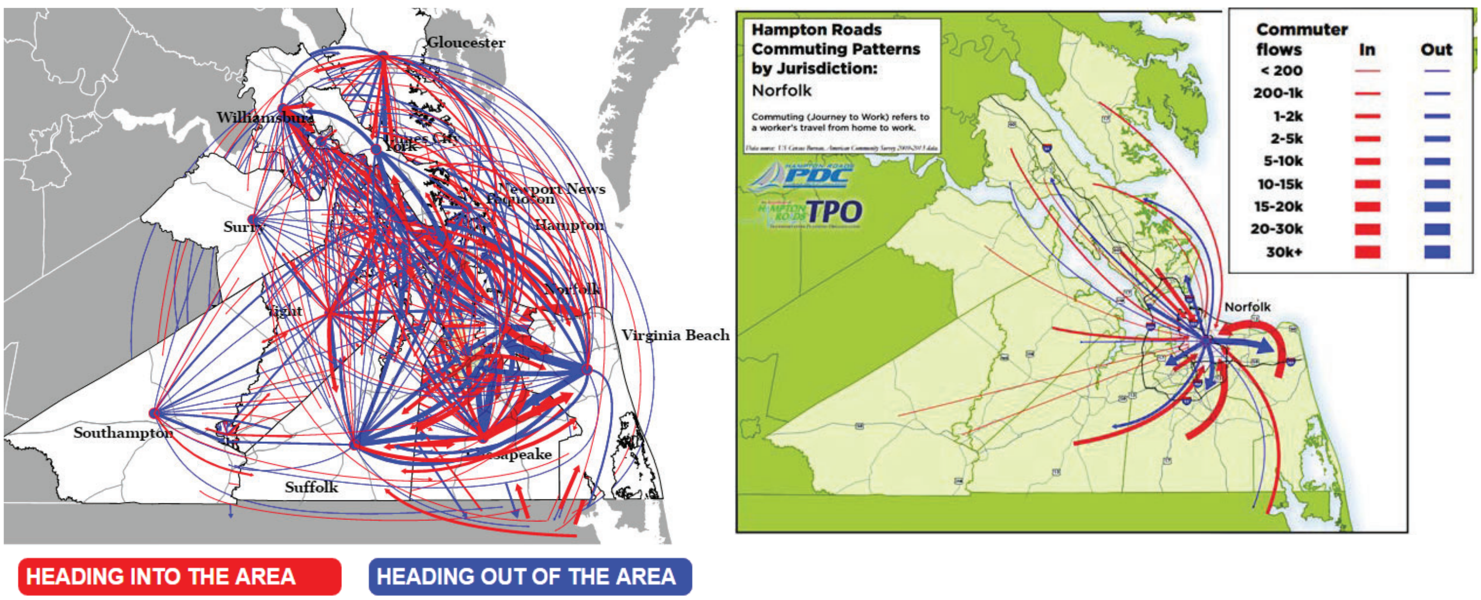


Figure 4. Commuting pathways within Hampton Roads (left panel) and within Norfolk (right panel) (Sources: Hampton Roads Transportation Planning Organization; using 2009-2013 data from U.S. Census Bureau; Hampton Roads Planning District Commission)

The majority of the population commutes for work into Norfolk from communities to the southwest, south, and east of the city. Figure 4 depicts the regional commuting patterns to and from Norfolk, based on data

[16] HRTPO (2016).
[17] LiDAR data was collected from the region from 2011 to 2014 and referenced against the North American Vertical Datum 1988 (NAVD 88). NAVD88 serves as a reference for measuring elevation. LiDAR provides elevation for bare earth. The GIS elevation has a spatial resolution of 5 feet by 5 feet.
[18] HRTPO (2013a).
[19] Pascale (2016).

from the U.S. Census Bureau in 2009 to 2013.[20] Pretty Lakes, located in western Norfolk and eastern Virginia Beach, represents a significant portion of commuters. However, the longest commutes are traveled by a smaller subset of the population generally to the west and north of the city. The more heavily traveled routes likely require additional maintenance and upkeep, and loss of such routes from extreme weather events will likely have a larger economic impact on the region than the less traveled routes.

Condition. Virginia earned a "D" on the Report Card of America's Infrastructure in 2015.[21] In 2008, 6 percent of major roads were classified as poor, about a quarter were classified as deficient, and 18 percent were considered only mediocre.[22] Over 20 percent of Virginia's roads score lower than a 2.5 on the Present Serviceability Rating, generally regarded as the lowest acceptable road score for comfortable driving.[23] This information is not available disaggregated to the regional or city jurisdictional level.

Congress in the recent law titled, Moving Ahead for Progress in the 21st Century (MAP-21) (Pub. L. 112–141, July 6, 2012) introduced pavement condition metrics for roadways that qualify for federal funding. This covers pavements on the Interstate System and on the non-interstate National Highway System (NHS). The performance measures include roughness, cracking, rutting, and faulting.

[20] United States Census Bureau, "American Community Survey (ACS)."
[21] American Society of Civil Engineers (2016).
[22] The Road Information Program (TRIP) (2011).
[23] Research and Innovative Technology Administration (RITA) (2011). It costs motorists about $1.8 billion a year to drive on roads that need to be repaired, which equates to $344 per motorist per year. If these roads are repaired or reconstructed (e.g., in response to adaptive measures), the reduction of costs would be a benefit to motorists.

Table 4. Proposed thresholds for pavement condition metrics (Source: FHWA (2013b))

Surface Type	Metric	Metric Range	Proposed Rating
All Pavements	International Roughness Index	<95	Good
		95-170 (under 1 mill pop)	Fair
		95-220 (urbanized, over 1 mill pop)	
		>170 (under 1 mill pop)	Poor
		>220 (urbanized, over 1 mill pop)	
Asphalt Pavement, Jointed Concrete	Cracking %	< 5%	Good
		5-10%	Fair
		>10 %	Poor
Asphalt Pavement	Rutting	<.20	Good
		.20-.40	Fair
		>.40	Poor
Jointed Concrete Pavement	Faulting	<.05	Good
		.05-.15	Fair
		>.15	Poor
Continuously Reinforced Concrete Pavement	Cracking %	< 5%	Good
		5-10%	Fair
		>10 %	Poor

A recent report for the Commonwealth of Virginia analyzed the pavement conditions for VDOT districts, including the HR. [24] Pavement condition is based on the aggregate of a load-related distress rating (e.g., fatigue, cracking, rutting, etc.) and a non-load distress rating (e.g., longitudinal joint separation, etc.) where a value of 60 is considered "deficient" and warrants further evaluation. Pavement roughness is describes as ride quality where values above 140 are considered poor quality for interstate and primary roads and values above 220 are considered poor quality for secondary roads.

Overall, roads in HR were observed to be in relatively good condition. Table 5 shows the percentage of roads that are in sufficient condition (i.e., roads rating at fair or better). Interstates and primary roads exceed the Virginia target of 82 percent, with 91.1 percent and 87.3 percent on pavement condition, respectively. They also exceed the roughness target of 85 percent, with 98.8 percent and 90.4 percent. Secondary roads are in worse condition, though they still exceed the target of 65 percent for pavement condition. There is no target for roughness, but only 58.8 percent of secondary roads are rated fair or higher.

[24] VDOT (2015b).

Table 5. Percent of pavement condition and roughness rated as fair or better for HR in 2015 (Source: VDOT (2015b))

	PAVEMENT CONDITION (%)		PAVEMENT ROUGHNESS (%)	
	HR	Target	HR	Target
INTERSTATE	91.1	82	89.8	85
PRIMARY	87.3	82	90.4	85
SECONDARY	75.9	65	58.8	-

Table 6 provides the number of lane miles that are deficient (i.e. they are rated as poor or very poor) based on scoring of pavement condition and pavement roughness. Interstates have the lowest lane mileage that is deficient, followed by primary, and then by secondary. Note that the numbers for secondary are understated, as they do not include all secondary roads in the region, just a survey of 1,252 miles.

Table 6. Lane miles in HR that scored deficient for pavement condition and pavement roughness in 2015 (Source: VDOT (2015b))

	PAVEMENT CONDITION	PAVEMENT ROUGHNESS
INTERSTATE	70	79
PRIMARY	223	166
SECONDARY*	302	497

**Out of a survey of 1252 miles*

Valuation. VDOT provides recommendations for calculating construction costs of roadways and valuation of existing roadways. The costs of roadways is calculated by multiplying the miles of roadway to be built by the roadway type cost factor. The cost factors are based on valuation in the year 2000. VDOT recommends applying the Bureau of Labor Statistics Consumer Price Index to inflate these costs to today's dollars.[25] The costs per mile range from $237,208 (FY2000) for a secondary roadway to $1,874,055 (FY2000) for an interstate highway (see Table 7). Similar information is not available for estimating the cost to reconstruct roadways. However, such information may be gathered from compiling reconstruction costs associated with past transportation projects.

Table 7. Costs to construct 1 lane mile for various types of roadways (Source: using cost factors from VDOT (2015a))

ROADWAY	AVERAGE COST TO CONSTRUCT 1 LANE MILE (FY2000)
INTERSTATE	$1,874,055
PRIMARY	$768,627
SECONDARY	$237,208
URBAN	$799,775

[25] Bureau of Labor Statistics Consumer Price Index is found here: http://www.bls.gov/cpi/.

VDOT provides a methodology to estimate the valuation of existing roadways. First, determine lane miles by roadway type and year. Second, subtract any lane miles related to bridges and tunnels to obtain the roadway lane miles. Third, for each type of roadway comprised in the roadway lane miles, identify the costs (FY2000) to construct a lane mile of road and apply a deflation factor by year using the Consumer Price Index. For depreciation, VDOT suggests roads have a useful life of 30 years and to apply a straight line depreciation method to estimate value.

Another source of valuation information is FEMA's Hazards-United States Multi-Hazard tool (HAZUS-MH). HAZUS-MH is a suite of three models that estimate losses associated with earthquakes, hurricane wind, and flood. The flood model considers both coastal and riverine flooding. HAZUS-MH includes information concerning transportation lifelines that may be useful for an economic quantification, such as valuation data on roadways. HAZUS-MH data suggests that the total valuation for Norfolk highways is approximately $1.4 billion, with urban principal arterial representing about 60 percent of total valuation (see Table 8). This information can be accessed and analyzed for other regions within HR.

Table 8. Total valuation of Norfolk highways, by category (Source: Hazards United States – Multi Hazard (HAZUS-MH))

ROADWAY	TOTAL LENGTH (CENTERLINE MILES)	TOTAL LANE MILES (MILES)	TOTAL REPLACEMENT COST ($000)
UNKNOWN	10.9	No data	$72,537
URBAN FREEWAY OR EXPRESSWAY	0.3	0.6	$986
URBAN INTERSTATE	41.1	275.5	$470,104
URBAN MINOR ARTERIAL	4.1	14.6	$24,310
URBAN PRINCIPAL ARTERIAL	116.1	229.7	$839,847
TOTAL	**172.4**	**520.3**	**$1,407,784**

Bridges

Ownership & Inventory. The 2012 Hampton Roads Transportation Planning Organization (HRTPO) *Regional Bridge Study* describes the prominent role bridges play in the HR landscape. These bridges range from major spans such as the Coleman Bridge, James River Bridge, and High Rise Bridge, the Interstate system bridges, and many smaller bridges that provide grade separation for principal arterials, and smaller structures such as culverts that span the myriad of creeks, swamps and waterways in the regions.[26] Water divides Hampton

[26] According to the HRTPO (2012b) report*:* HR ranked 21st highest in median bridge age among the 35 comparable area (with population between 1-3 million). Chesapeake, Norfolk, Southampton, Suffolk and Virginia Beach have the largest number of bridges (between 118 and 188 bridges each) with ages around 37 or slightly older.

Roads into many sub-regions, making bridges a prominent feature of the HR landscape, totaling 1,223.[27] Indeed, HR has more lane-miles of bridges than *all* other metropolitan areas in Virginia, and many others nationally.[28]

There are a number of bridge types in HR and Norfolk (see Table 9). HR bridges are largely stringer/multi-beam or girder system bridges (65 percent) (also representing 88 percent of Norfolk bridges). Considering the bridge type is important, as a climate-sensitivity analysis is to determine if the type of bridge introduces specific sensitivities to a changing climate. For example, a storm surge event could damage a movable bridge so that the bridge is stuck in either the open position, halting roadway traffic, or in the closed position, stopping ship traffic.

Table 9. Bridge type and number in HR and Norfolk (based on data from the 2015 NBI)

	HAMPTON ROADS		NORFOLK	
STRUCTURE TYPE	# OF BRIDGES	% OF BRIDGES	# OF BRIDGES	% OF BRIDGES
SLAB	99	8.15	4	2.11
STRINGER/MULTI-BEAM OR GIRDER	788	64.91	167	87.89
GIRDER AND FLOORBEAM SYSTEM	7	0.58	-	-
TEE BEAM	39	3.21	1	0.53
BOX BEAM OR GIRDERS – MULTIPLE	48	3.95	5	2.63
BOX BEAM OR GIRDERS - SINGLE OR SPREAD	1	0.08	-	-
FRAME (EXCEPT FRAME CULVERTS)	4	0.33	-	-
TRUSS – DECK	2	0.16	-	-
TRUSS – THRU	3	0.25	-	-
ARCH – DECK	13	1.07	-	-
ARCH – THRU	4	0.33	-	-
MOVABLE - LIFT	3	0.25	-	-
MOVABLE - BASCULE	6	0.49	2	1.05
MOVABLE - SWING	3	0.25	-	-
CULVERT (INCLUDES FRAME CULVERTS)[29]	193	15.90	11	5.79
OTHER	1	0.08	-	-
TOTAL	**1214**		**190**	

[27] HRTPO (2012b). 99 percent of these bridges are captured in the 2015 NBI (i.e., 1,214 bridges of the total 1,223 bridges identified by the HRTPO (2012b) report).
[28] HRTPO (2012a).
[29] The FHWA Recording and Coding Guide defines culverts as "A structure designed hydraulically to take advantage of submergence to increase hydraulic capacity. Culverts, as distinguished from bridges, are usually covered with embankment and are composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert. Culverts may qualify to be considered "bridge" length." The culverts in this analysis are culverts over 20 feet in length.

Within HR, the majority of the 1,223 bridges are owned by VDOT (63 percent) and municipalities (33 percent).[30] VDOT owns and maintains bridges on the Interstate system and those outside of cities. Cities own and maintain bridges located within the city but not located on the Interstate system. A much smaller number of bridges (2.7 percent) are owned by Federal Government, including the National Park Service and the Army Corps of Engineers. The remaining bridges (1.4 percent) are owned and maintained by the private sector or state commissions. In Virginia, bridges for railroad travel are owned and maintained by the railroad companies.[31]

The HRTPO has available a GIS shapefile of the location of elevated structures that provide roadway travel (e.g., bridges and overpasses). For some of these structures, HRTPO realized the land at bare earth (below the structure elevation) was being identified as the structure elevation and used aerial photography to correct this effect when reviewing inundation flood scenarios.[32] In addition, VDOT provides shapefiles of the spatial extent and location of bridges and culverts at or greater than 20 feet in length (some municipalities collect spatial information for the smaller culverts).[33]

Use. The region is reliant on bridges to move both people and goods. The cumulative Average Daily Traffic (ADT) for bridges in HR is close to 24 million, as shown in Table 10. Table 10 shows that 77 percent of the traffic in HR and 91 percent of the traffic in Norfolk crosses over Stringer/multi-beam or girder bridges.

[30] HRTPO (2015b).
[31] Per communication with Rodolfo Maruri, P.E., Federal Highway Administration, Virginia Division. Richmond, VA.
[32] HRTPO (2016).
[33] Per communication with representatives from HRTPO and HRPDC.

Table 10. Average daily traffic by bridge type in HR and Norfolk (2015 NBI)

STRUCTURE TYPE	HAMPTON ROADS ADT OF BRIDGES	HAMPTON ROADS PERCENT OF CUMULATIVE ADT	NORFOLK ADT OF BRIDGES	NORFOLK PERCENT OF CUMULATIVE ADT
SLAB	720,170	3.01	47,800	0.62
STRINGER/MULTI-BEAM OR GIRDER	18,410,042	77.03	7,013,419	90.58
GIRDER AND FLOORBEAM SYSTEM	171,044	0.72	-	-
TEE BEAM	224,082	0.94	9,300	0.12
BOX BEAM OR GIRDERS - MULTIPLE	645,445	2.70	163,550	2.11
BOX BEAM OR GIRDERS - SINGLE OR SPREAD	9,943	0.04	-	-
FRAME (EXCEPT FRAME CULVERTS)	72,391	0.30	-	-
TRUSS - DECK	100	0.00	-	-
TRUSS - THRU	3,759	0.02	-	-
ARCH - DECK	139,542	0.58	-	-
ARCH - THRU	7,817	0.03	-	-
MOVABLE - LIFT	57,251	0.24	-	-
MOVABLE - BASCULE	238,177	1.00	94,136	1.22
MOVABLE - SWING	70,619	0.30	-	-
CULVERT (INCLUDES FRAME CULVERTS)	3,120,808	13.06	414,546	5.35
OTHER	8,000	0.03	-	-
TOTAL	**23,899,190**		**7,742,751**	

In HR, the 2030 forecast suggest about a doubling of traffic in the HR compared to today (see

Table 11). Comparatively, Norfolk accounts for nearly one third of the vehicles, with an ADT of almost 8 million, including about 400,000 trucks (see Table 12). ADT in Norfolk is expected to more than double by 2030, to about 19 million vehicles.

Table 11. Present and future use of HR Bridges (Source: 2015 NBI)

FUNCTIONAL CLASSIFICATION	NUMBER OF HR BRIDGES	TOTAL LENGTH OF HR BRIDGES (METERS)	AVERAGE DAILY TRAFFIC (NUMBER OF VEHICLES)	2030 FORCAST OF AVERAGE DAILY TRAFFIC (NUMBER OF VEHICLES)	AVERAGE DAILY TRUCK TRAFFIC (NUMBER OF VEHICLES)
PRINCIPAL ARTERIAL - INTERSTATE	3,561	56,291	15,413,840	31,803,733	383,627
PRINCIPAL ARTERIAL - OTHER FREEWAYS OR EXPRESSWAYS	1,074	15,343	1,897,667	2,994,750	143,037
OTHER PRINCIPAL ARTERIAL	1,708	24,534	3,017,999	5,841,851	221,485
MINOR ARTERIAL	2,654	16,604	2,515,869	4,657,286	163,115
COLLECTOR	2,280	9,752	708,229	1,200,296	33,620
LOCAL	3,609	6,844	345,586	550,811	11,550
TOTAL	**14,886**	**129,368**	**23,899,190**	**47,048,727**	**956,434**

Table 12. Present and future use of Norfolk Bridges (Source: 2015 NBI)

FUNCTIONAL CLASSIFICATION	NUMBER OF NORFOLK BRIDGES	TOTAL LENGTH OF NORFOLK BRIDGES (METERS)	AVERAGE DAILY TRAFFIC, (NUMBER OF VEHICLES)	2030 FORECAST OF AVERAGE DAILY TRAFFIC (NUMBER OF VEHICLES)	AVERAGE DAILY TRUCK TRAFFIC (NUMBER OF VEHICLES)
PRINCIPAL ARTERIAL – INTERSTATE	135	17,383	6,538,987	16,858,663	330,365
PRINCIPAL ARTERIAL - OTHER FREEWAYS OR EXPRESSWAYS	2	202	27,090	42,500	984
OTHER PRINCIPAL ARTERIAL	32	5,073	935,164	1,570,500	52,135
MINOR ARTERIAL	12	2,203	155,348	244,500	8,081
COLLECTOR	6	364	58,390	72,500	5,125
LOCAL	3	48	7,276	9,425	1,110
GRAND TOTAL	**190**	**25,272**	**7,722,255**	**18,798,088**	**397,800**

Condition. Bridges in HR are aging with about 10 percent of the bridge inventory built prior to 1950, as are many other bridges in the nation.[34] The average bridge age in HR is 37 years (as of 2012), slightly lower than comparable metro areas.[35] Two metrics have been used in the past to quantify bridge condition: structural deficiency and scour rating. Recently, with the 2012 law Moving Ahead for Progress in the 21st Century (MAP-21), bridge performance measures were adopted that include deck condition, superstructure, substructure, and culverts.[36] This section considers all of these metrics in summarizing bridge condition.[37]

Structural deficiency. Standard engineering criteria for bridge "deficiency" consist of ratings for "structural deficiency" and "functional obsolescence." Bridges are labeled as structurally deficient when one or more major component is deteriorating (see Figure 5 for identification of deficient bridges).[38] A functionally obsolete bridge is a bridge that does not meet current design standards (i.e., it is not an indicator of condition). Such labels do not necessarily mean the bridge is unsafe but may require operational restrictions. According to the HRTPO Regional Bridge Study, adding up the two classifications, a total of 456 bridges in HR (37 percent) are classified as "deficient," making HR the third highest nationwide in its size class in this category.[39] Table 13 compares the HR bridge condition rating with the results of a recent GAO report stating that nearly a quarter of the Nation's bridges are deficient (10 percent as structurally deficient; and 14 percent as functionally obsolete).[40] The table underscores the fact that while 37 percent of HR's 1,223 bridges are classified as deficient, only 6.3 percent (77 bridges in HR) are classified as structurally deficient. Comparing the nation's ratio of 10 percent with the 6.3 percent rate of structurally deficient bridges in HR shows that condition of bridges in HR does not indicate above-average structural deficiencies.

Table 13. Highway bridge condition ratings in HR (Sources: GAO (2015); HRTPO (2012b))

CONDITION CATEGORY	COUNT OF HR BRIDGES	% OF HR BRIDGES	% OF BRIDGES NATIONALLY
FUNCTIONALLY OBSOLETE	379	31%	14%
STRUCTURALLY DEFICIENT	77	6.3%	10%
TOTAL FUNCTIONAL AND STRUCTURAL DEFICIENCY	**456**	**37%**	**24%**

[34] HRTPO (2012b).
[35] HRTPO (2012b).
[36] FHWA (2016a).
[37] In addition, see VDOT's Supplement to the AASHTO Manual for Bridge Element Inspection (2016): http://www.virginiadot.org/business/resources/bridge/VDOT_Suppl_to_the_AASHTO_Manual_for_Bridge_Element_Insp_2016.pdf.
[38] Appendix D describes the standards for bridge condition classification.
[39] According to the HRTPO report, HR is the third highest of comparable 35 metropolitan areas in percentage of deficient bridges (after Providence and Pittsburgh) in its size class. HRTPO (2012b).
[40] U. S. Government Accountability Office (GAO) (2015).

The National Bridge Inventory (NBI) data in the National Transportation Atlas Database show that 3 of 190 Norfolk bridges (1.6 percent) are structurally deficient.

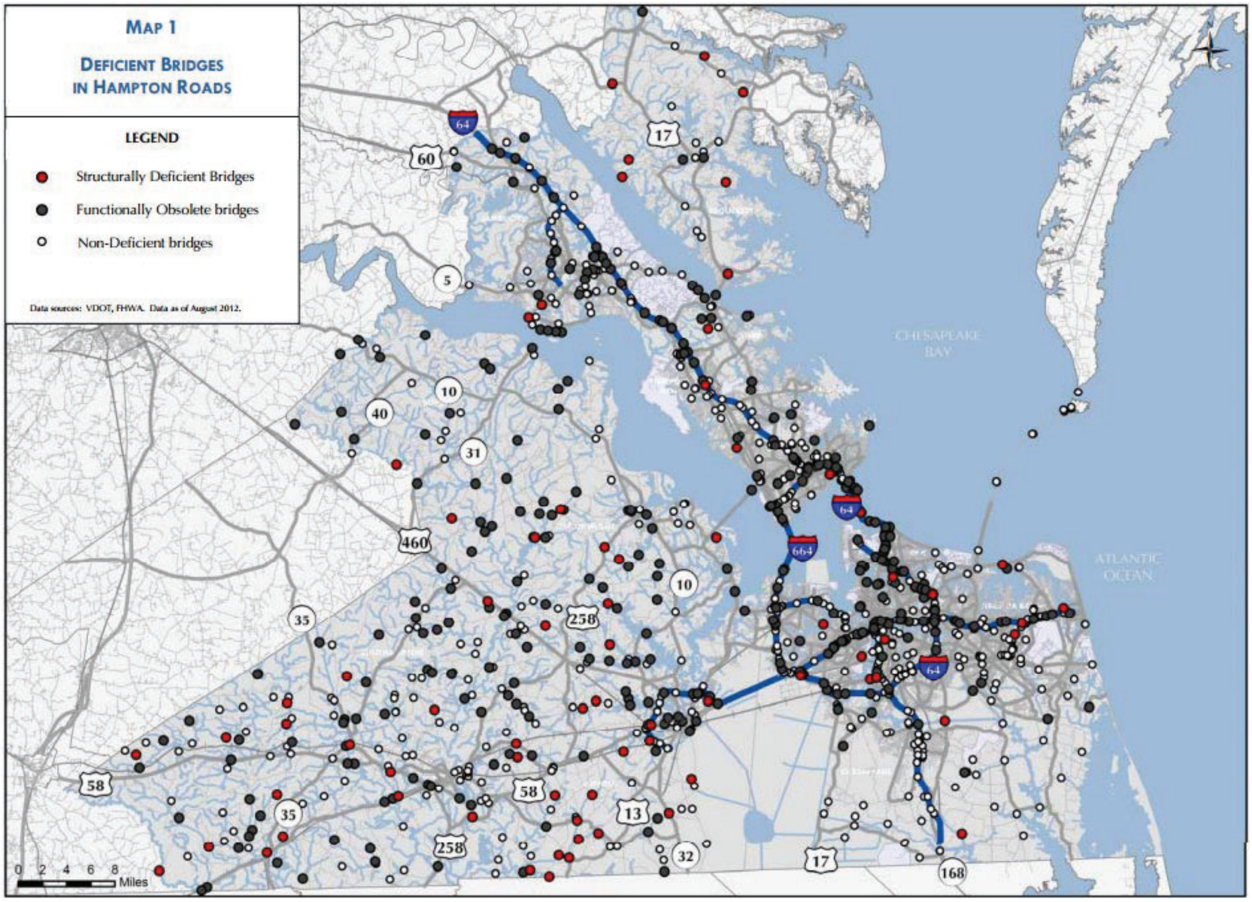


Figure 5. Deficient HR bridges (Source: HRTPO (2012b))

Bridge Scour. For bridges built over water that have underwater substructures, there is a code for Scour Critical Bridges that rates both bridge condition and risk of scour.[41] The Hazards United States – Multi Hazard (HAZUS-MH) bridge deficiency data are based on the Scour Critical Bridges codes from the NBI. The codes roughly describe the condition of the bridge and the risk of the bridge. Of the 190 bridges in Norfolk, 141 bridges are given a scour rating that indicates the bridge is not located over water. All of the remaining bridges that are over water in Norfolk are in acceptable condition.[42]

[41] Bridge scour is the erosive action of moving water carrying away sediment around the bridge pier or abutment, comprising bridge integrity.

[42] Bridge scour codes of 0, 1, 2, 3, 6, U, or T suggest some level of concern regarding scour. Bridge scour codes of 5, 8, N, and 0 are not of concern. In Hampton Roads, bridges have a scour code of 5, 8, or N. Appendix D contains the complete list of all the NBI Scour Critical Bridges codes.

MAP-21 Performance Measures. MAP-21 performance measures require ratings of the deck, superstructure, and substructure condition for bridges (see Figure 6), and conditions for culverts are also rated. The ratings are on a scale from 0 to 9, where 0 is a bridge with a deck in failure condition and 9 is a bridge with a deck in excellent condition.[43] The majority of bridges scored at least a 5 in deck, superstructure, and substructure condition (see Table 14). Culvert condition was largely not applicable or in fair/good condition. The overall bridge condition suggests HR bridges are in fair/good condition.

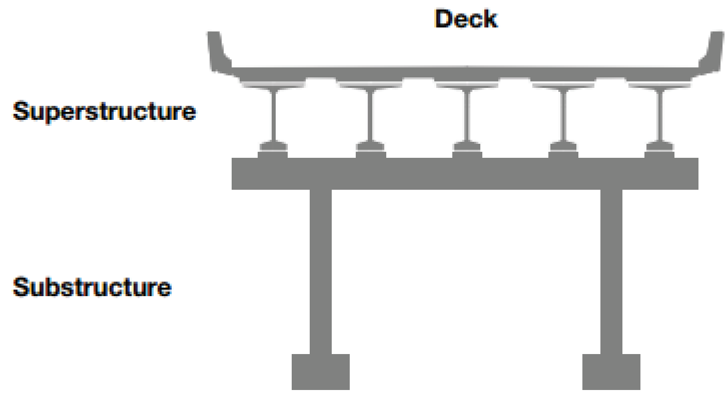


Figure 6. Anatomy of a bridge (WSDOT (2015))

Table 14. MAP-21 Performance measures for HR bridges (Source: 2015 NBI)

CONDITION	CULVERT		DECK		SUPERSTRUCTURE		SUBSTRUCTURE		BRIDGE CONDITION*	
	# of Culverts	% of Culverts	# of Bridges	% of Bridges	# of Bridges	% of Bridges	# of Bridges	% of Bridges	# of Bridges	% of Bridges
GOOD (7, 8, 9)	81	6.67	450	37.07	436	35.91	381	31.38	322	26.52
FAIR (4, 5, 6)	112	9.23	562	46.29	580	47.78	640	52.72	886	72.98
POOR (1, 2, 3)	-	-	2	0.16	5	0.41	-	-	6	0.49
NOT APPLICABLE	1021	84.10	200	16.47	193	15.90	193	15.90	-	-
TOTAL	**1214**		**1214**		**1214**		**1214**		**1214**	

**A bridge is rated in good conditions if all 3 bridge elements are rated at good; in fair condition if the lowest element is between 4 to 6; in poor condition if any element if below a 4.*

[43] See Appendix D for a complete description of each of the codes for deck condition.

Bridges in Norfolk are rated at least in fair condition specifically for deck and substructure conditions (see Table 15).

Table 15. MAP-21 Performance measures for Norfolk bridges (Source: 2015 NBI)

CONDITION	CULVERT		DECK		SUPERSTRUCTURE		SUBSTRUCTURE		BRIDGE CONDITION*	
	# of Culverts	% of Culverts	# of Bridges	% of Bridges	# of Bridges	% of Bridges	# of Bridges	% of Bridges	# of Bridges	% of Bridges
GOOD (7, 8, 9)	4	2.11	65	34.21	57	30.00	50	26.32	28	14.74
FAIR (4, 5, 6)	7	3.68	114	60.00	122	64.21	129	67.89	162	85.26
POOR (1, 2, 3)	-	-	-	-	-	-	-	-	-	-
NOT APPLICABLE	179	94.21	11	5.79	11	5.79	11	5.79	-	-
TOTAL	**190**		**190**		**190**		**190**		**190**	

**A bridge is rated in good conditions if all 3 bridge elements are rated at good; in fair condition if the lowest element is between 4 to 6; in poor condition if any element if below a 4.*

Flooding Sensitivities

Bridges/tunnels. As flooding is projected to increase in HR, the following historic flood issues for bridges/tunnels offer helpful insight:

- The elevation and structural integrity of the approach to a bridge tends to represent a majority of closure risk (many bridges are sufficiently elevated above flood waters).
- Bridge-tunnels to the Virginia Peninsula historically experience flooding and closures.

Source: Sandia National Laboratories (2011).

Culverts. Design standards can provide some indication of possible sensitivities to climate-related stressors. For VA roadways, drawing from the Virginia Department of Transportation (VDOT) Drainage Manual, culverts are hydraulically designed at a minimum to operate under specific flood conditions to ensure maintenance of traffic flow and convenience of the highway user (see Table below). However, the design should allow for greater floods if there is the potential for adjacent property damage, loss of human life, or heavy financial loss. In addition, if the roadway is/will be located in the National Flood Insurance Program's (NFIP) 100-year floodplain, then the culvert must be part of a designed system that allows for the 100-year flood without raising the water surface elevation more than 1 foot. This is relevant when considering whether the magnitude of flood frequencies (annual risk) is going to change under a future climate and hence, suggest alternative adaptation options for managing flows.

Design standards for culverts in the Commonwealth of Virginia

Roadway	Flood Frequency (Annual Risk)
Interstate	50-year (2%)
Primary & Arterial	25-year (4%)
Secondary	10-year (10%)

Source: VDOT (2002).

Valuation. VDOT recommends using $75 (FY2000) as the average cost to construct one square foot of bridge.[44] To value the existing bridge, VDOT recommends the following methodology: (1) identify the year of the bridge; (2) calculate the square footage of the bridge; (3) multiply the square footage of the bridge by the cost to construct 1 square foot of bridge ($75/ft^2); (4) apply a deflation factor by year using the Consumer Price Index. For depreciation, VDOT suggests bridges have a useful life of 50 years and to apply a straight line depreciation method to estimate value. VDOT also has formulas for the cost of each foot of bridge elevation.[45] VDOT also recommends using the cost factor $100/ft^2 (FY2000) to estimate the average costs of building a culvert. The methodologies for estimating the costs for building a culvert based on today's dollars and to value existing culverts follows that detailed here for roads. For depreciation, VDOT suggests culverts have a useful life of 50 years.

[44] VDOT (2015a).
[45] Per communication with John Mazur at FHWA.

HAZUS-MH database provides another source of bridge valuation, representing replacement costs. A drawback of using HAZUS-MH is that it is based on information collected in 2001. For example, in Norfolk, the total valuation of $591.2M for the 190 highway bridges suggests an average cost of $3.1M to rebuild each highway bridge. Many DOT experts have commented on the low valuation of the regional bridge assets in the HAZUS-MH database. The value is also low because not all bridges in the dataset had valuations. This report recognizes this downward bias. This information can be accessed and analyzed for other regions within HR.

Valuation of rail bridges in HR, as documented in HAZUS-MH is even lower in value than what the experts view as reasonable. For example, Table 16 shows the HAZUS-MH valuation of the five rail bridges in Norfolk, along with the year built and their valuation, but no condition ranking. It shows a reported valuation of just $321,000 for the five railroad bridges (presumably all owned privately by the railroads), suggesting an average cost of $64,200 to rebuild a single bridge should it fail. The inconsistent figures for HAZUS-MH valuation of the unit costs for highway- and rail-bridge stock, and the overall down-side bias of the database's highway asset valuation, suggest that the validity of the underlying data needs to be verified.

Table 16. Railway Bridges in Norfolk (Sources: HAZUS-MH; 2001 NBI)

NAME OF BRIDGE	YEAR BUILT	HAZUS-MH VALUATION
COLLY AVE U NS RA	1972	$67,000
N&W RAILWAY	1952	$64,000
NS RAILWAY	1940	$53,000
TDWTR DR U NS RAI	1956	$64,000
VA BEACH BLVD U NS	1959	$73,000
GRAND TOTAL		**$321,000**

Regardless of accuracy of the valuation of the bridges, bridges are particularly costly to build and maintain. Funding has not kept up with bridge maintenance needs.[46] This is concerning because it is more cost effective to keep bridges in good condition than to repair bridges once they are in poor condition. The FHWA Bridge Preservation Guide states "[p]reservation activities often cost much less than major reconstruction or replacement activities."[47] Bridge length is a key factor in the engineering complexity and rebuilding costs. The 1,223 bridges in HR are particularly long: in total they span 565,000 feet, or an average of 460 feet for each bridge.[48] Given the high costs of bridge maintenance, the assessment of the condition of HR bridges as part of the region's climate change adaptation planning process plays a prominent role.

Movable Bridges. There are three main types of movable bridges: lift, bascule, and swing. Lift bridges raise the deck straight up above the waterway to allow boats to pass through. Bascule bridges rotate portions of

[46] FHWA (2011a).
[47] FHWA (2011a).,
[48] According to HRTPO (2012b): Placed end-to-end, they span over 107 miles in total. The total deck area of HR bridges is 28,227,000 square feet. This ranks HR 8th highest among 35 comparable metropolitan areas (after New Orleans, St. Louis, Kansas City, Austin, San Antonio, Baltimore, and Pittsburgh).

the deck vertically with a counterweight. Swing bridges rotate a portion of the deck horizontally 90 degrees so boats can pass on either side.

Though non-movable bridges represent by far the greatest percentage of daily traffic, movable bridges are important to the region and can provide alternative routes (see Table 17). While the twelve movable bridges in HR make up slightly less than 1 percent of bridges in HR, they account for over 1.5 percent of average daily bridge traffic in the region, servicing some 366,000 vehicles every day. Movable bridges allow traffic to move both over and through waterways while avoiding high construction costs that come with building a stationary bridge high enough to allow for waterway traffic. However, they are more expensive to operate, as they require machinery, staff, and extensive maintenance.

Table 17. Average number, percent, and average daily traffic (hour) by bridge type (move-able versus non-movable) in HR and Norfolk (Source: 2015 NBI)

STRUCTURE TYPE	# OF BRIDGES HR	% BRIDGES HR	# OF BRIDGES NORFOLK	% OF BRIDGES NORFOLK
MOVABLE-LIFT	3	0.25	0	0.00
MOVABLE-BASCULE	6	0.49	2	1.05
MOVABLE-SWING	3	0.25	0	0.00
NON-MOVABLE	1,202	99.01	188	98.95
TOTAL	**1,214**		**190**	
STRUCTURE TYPE	**ADT of Bridges HR**	**% ADT HR**	**ADT of Bridges Norfolk**	**% ADT Norfolk**
MOVABLE-LIFT	57,251.00	0.24	-	-
MOVABLE-BASCULE	238,177.00	1.00	94,136.00	1.22
MOVABLE-SWING	70,619.00	0.30	-	-
NON-MOVABLE	23,533,143.00	98.47	7,648,615.00	98.78
TOTAL	**23,899,190.00**		**7,742,751.00**	

Five of the movable bridges account for more than 75 percent of average daily traffic on movable bridges in HR. They are the Berkley Bridge, the High Rise Bridge, the James River Bridge, the Gilmerton Bridge, and the Coleman Bridge. Three of these bridges (Berkley, High Rise, and Gilmerton) cross the Elizabeth River and serve as important alternate routes to the Downtown and Midtown Tunnels. The James River Bridge is used as an alternate to the HRBT and MMBT when they are congested.[49] These movable bridges are not scour critical, and their deck conditions ranges from fair to good (see Table 18).

[49] VDOT (2016).

Table 18. Average daily traffic (number of vehicles), scour condition, and deck condition for critical movable bridges in HR (Sources: per communication with HRTPO/HRPDC; 2015 NBI)

BRIDGE	ADT OF BRIDGES (HR)	SCOUR CODE	DECK CONDITION
GILMERTON	31,000	5	7
JAMES RIVER	28,000	5	5
BERKLEY EAST BOUND	49,000	5	6
BERKLEY WEST BOUND	49,000	5	6
HIGH RISE	89,000	5	5
COLEMAN	32,000	8	6

A few questions of interest when comparing the costs of extreme weather impacts on movable bridges to non-movable bridges: Are movable bridges at greater risk to extreme weather events than non-movable bridges (e.g., can lines sag or the integrity of lines be comprised during heat events)? Do movable bridges incur greater costs when damaged by an extreme event and/or require longer repair time than non-movable bridges? Is there a greater economic consequence of damage to a movable bridges due to impact on both roadway and waterway traffic?

Tunnels

Ownership and Inventory. Like bridges, tunnels serve a critical role in connecting the HR region, enabling enhanced mobility since the first tunnel opening in 1952. Figure 7 shows the five major tunnel complexes that connect Hampton Roads, followed by a description of each asset in Table 19.

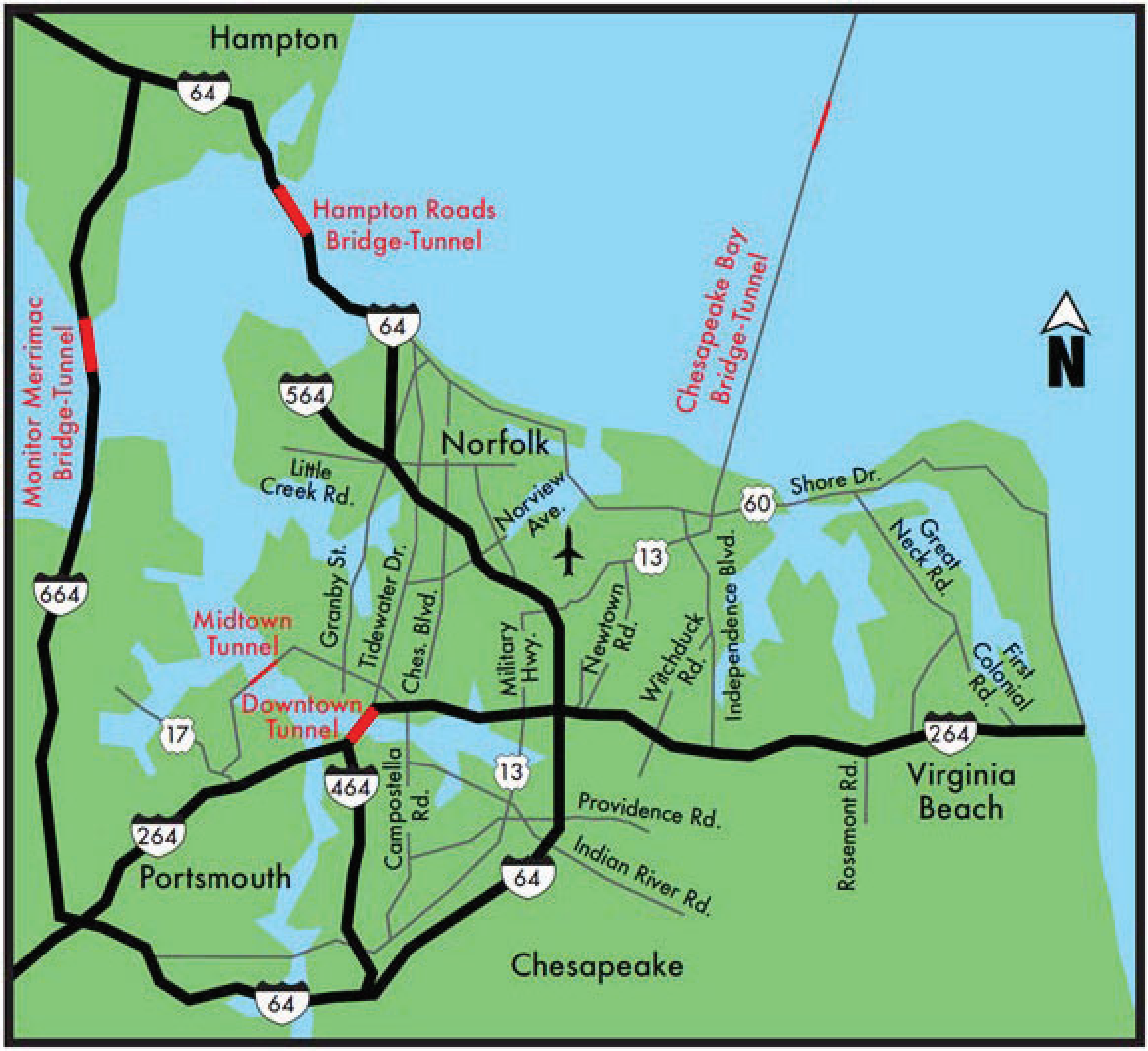


Figure 7. Tunnels connecting Hampton Roads. (Source: Old Dominion University annotated with tunnel locations)

Table 19. Description of the five major tunnel complexes in HR (Sources: VDOT (2016); per communication with HRTPO/HRPDC)

HAMPTON ROADS BRIDGE-TUNNEL / HRBT (I-64)

OPENED:	The first two-lane Hampton Roads Bridge-Tunnel (HRBT) opened in 1957; the second opened in 1976. Owned by VDOT.[50]
WATER CROSSING:	Spans Hampton Roads Harbor.
CONNECTS:	Connects Hampton and Newport News to Norfolk and Virginia Beach.
LENGTH:	3.5 miles
TRAFFIC VOLUME:	About 86,000 vehicles per day, more during the tourist season.[51] During heavy traffic, many motorists use the MMMBT on I-664 instead.

[50] Benefit from a VDOT continual maintenance and operations program; Per communication with VDOT.
[51] Traffic numbers for HRBT, MMMBT, Downtown, and Midtown tunnels are given in vehicles per month at VDOT's website, and were converted to per day values assuming a month has 30 days.

MONITOR-MERRIMAC MEMORIAL BRIDGE-TUNNEL / MMMBT (I-664)

OPENED:	The Monitor-Merrimac Memorial Bridge-Tunnel (MMMBT) opened in 1992 as a four-lane, dual-tunnel system. Owned by VDOT.[52]
WATER CROSSING:	Spans Hampton Roads Harbor.
CONNECTS:	Connects Newport News and Hampton to Suffolk and Chesapeake.
LENGTH:	4.6 miles
TRAFFIC VOLUME:	MMMBT serves as a less-congested alternative to the HRBT, normally carrying half the daily vehicular traffic volume of the HRBT (e.g., 62,000 vehicles per day).

DOWNTOWN TUNNEL (I-264)

OPENED:	The first two-lane Downtown Tunnel opened in 1952; the second opened in 1987. Leased to and operated by ERC.
WATER CROSSING:	Spans the Elizabeth River.
CONNECTS:	Links Norfolk and Portsmouth.
LENGTH:	0.65 miles
TRAFFIC VOLUME:	The Downtown Tunnel carries over 100,000 vehicles per day.

MIDTOWN TUNNEL (ROUTE 58)

OPENED:	The Midtown Tunnel opened in 1962 as the second tunnel connecting Norfolk and Portsmouth (built after the Downtown Tunnel). Leased to and operated by ERC. The second two-lane tunnel opened in 2016.
WATER CROSSING:	Spans the Elizabeth River.
CONNECTS:	Links Norfolk and Portsmouth.
LENGTH:	0.8 miles
TRAFFIC VOLUME:	The Midtown Tunnel carries over 33,000 vehicles per day.

CHESAPEAKE BAY BRIDGE-TUNNEL / CBBT (ROUTE 13)

OPENED:	The first two-lane Chesapeake Bay Bridge-Tunnel (CBBT) opened in 1964; the second parallel crossing opened in 1999. Privately owned.
WATER CROSSING:	Spans the mouth of Chesapeake Bay.
CONNECTS:	Connects Virginia Beach to Cape Charles in Northampton County.
LENGTH:	17.6 miles; the CBBT is the world's largest bridge-tunnel complex.
TRAFFIC VOLUME:	The CBBT had 3,796,973 vehicles in 2015, which is more than 10,000 per day.[53]

Use. The five major tunnels experience traffic volume from 10,000 to over 100,000 vehicles per day (see Table 19). With respect to tunnel capacity and congestion, four of the five major tunnel complexes in Hampton Roads were considered "choke points" (Figure 8). VDOT indicates that there have been recent improvements to the Midtown Tunnel and in response to the Elizabeth River Crossing Project. Improvements to the Midtown Tunnel occurred in response to flooding during Hurricane Isabel, including the reconstruction of the tunnel approach on the Norfolk-side from three feet to eight feet elevation to reduce future flooding of the tunnel

[53] Chesapeake Bay Bridge and Tunnel Commission (2016).

[53] Chesapeake Bay Bridge and Tunnel Commission (2016).

and account for future SLR.[54] Another tunnel will be added that will increase the number of lanes from 2 to 4. The expansion is expected to save the average user 30 minutes a day.[55] VDOT, since the 1990s, has also been examining options for adding a third Hampton Roads crossing for numerous reasons: to address congestion at the HRBT; provide transit access across the HR waterway; enhance evacuation capability; and increase port facilities access, among other objectives. Currently VDOT is re-evaluating options originally scoped in the *Hampton Roads Crossing Study* (2001), in cooperation with other federal/state authorities and the public. All of the design alternatives being considered involve the construction of new bridge/tunnel complexes, either adjacent to existing installations or in new locations.[56]

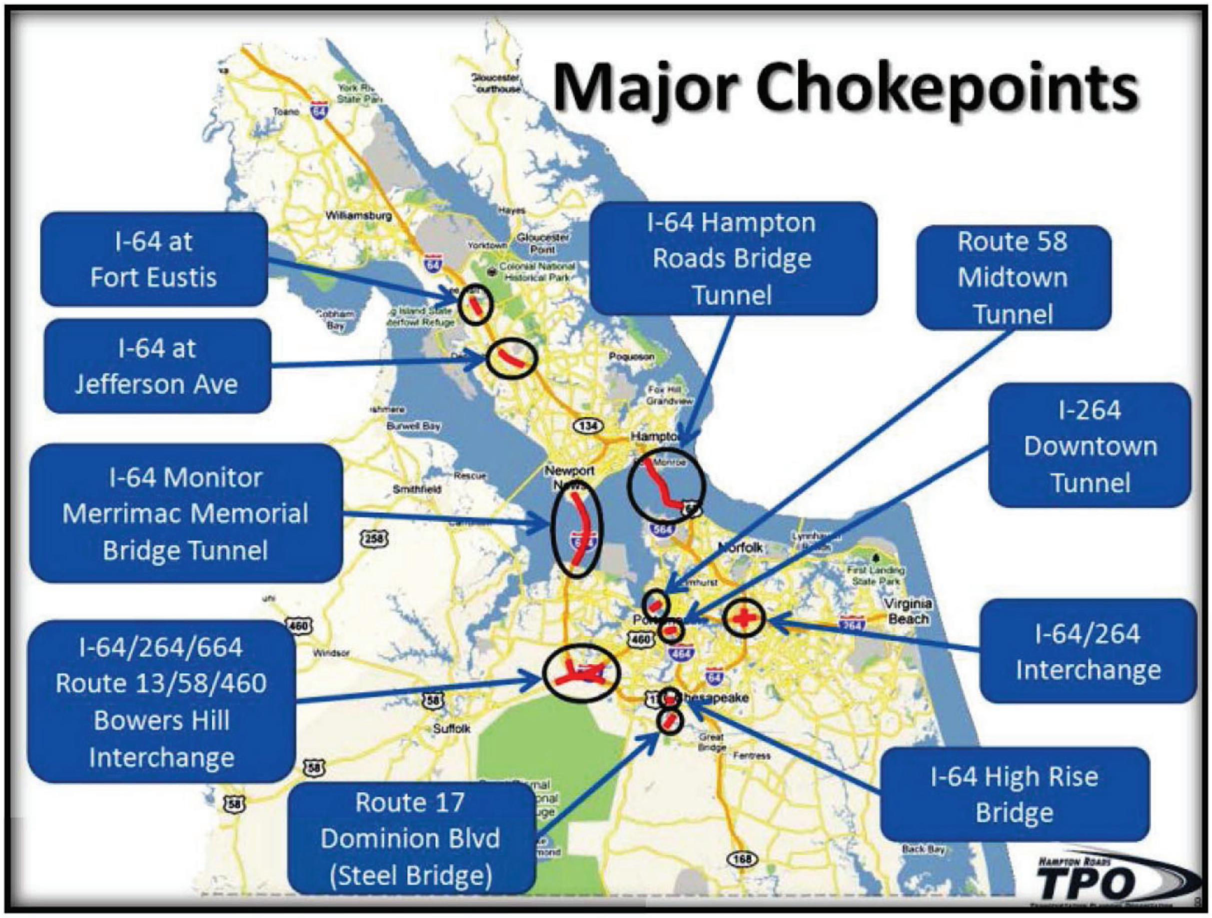
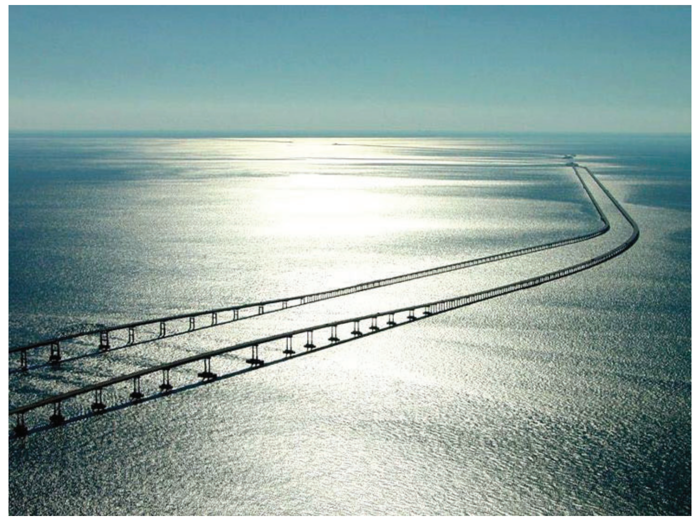


Figure 8. Major traffic chokepoints in Hampton Roads (Source: HRTPO)

[54] Per communication with John Mazur at FHWA.
[55] Elizabeth River Tunnels (2016a).
[56] VDOT (2001).

Condition. Unlike bridges, which have been overseen by the National Bridge Inspection Program (NBIP) for over 40 years, tunnels have not been subject to national inspection requirements or standards. In 2012 MAP-21 directed Federal Highway Administration (FHWA) to compile an inventory of the nation's tunnels and begin to develop a national database similar to the National Bridge Inventory (NBI). In addition to a new *National Tunnel Inventory (NTI)*, the law directed the establishment of new *National Tunnel Inspection Standards (NTIS),* to be modeled after the National Bridge Inspection Standards (NBIS) currently used to ensure the inspection of bridges throughout the country.[57] In 2015, final rulemaking for the NTIS was issued in addition to specifications for the NTI. However at the time of this report, complete national tunnel inventory data, including Federal information on tunnel health and condition, has not yet been released. Full data sets for the NTI are due to be submitted in the spring of 2018. The NTI will include a number of attributes that will be of interest to this report, including: average daily traffic, detour length, damage inspection, navigable waterway clearance, and tunnel or portal island protection. The NTI will also include condition data on various structures and systems in tunnels, such as liners, ventilation systems, lighting systems, and protective systems.



Hampton Roads tunnels are regularly inspected. Aside from obstructions caused by vehicular accidents, some common risks to tunnel operation include flooding (from weather events, groundwater infiltration, and pipe bursts), fire, pavement wear, and the compromised integrity of tunnel roof panels and other structural components.

The Midtown tunnel is currently undergoing an expansion that will include wider lanes and shoulders. This will allow emergency crews to clear broken or wrecked vehicles from the tunnel without a completely closing the tunnel.[58] The Downtown Tunnel is currently being rehabilitated. The rehabilitation includes tunnel fireproofing, a new ventilation system, LED lighting, tile and concrete repair, and updating signage.[59,60]

Bridge component characteristics of the three major HR tunnel/bridge complexes (HRBT, MMMBT, and CBBT) are captured in the NBI. Both the HRBT and the MMMBT have bridge segments that are classified as

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[57] FHWA (2015).
[58] WAVY (2016).
[59] Elizabeth River Tunnels (2016b)..
[60] A project being considered is changing the high-rise draw bridge (I-64) to a fix span bridge with enough elevation to allow for ships underneath. The elevation is to account for 5 feet of SLR. Per communication with John Mazur FHWA.

functionally obsolete, and part of the HRBT is classified as structurally deficient. The CBBT, which is privately operated, is classified in-whole as non-deficient.[61]

Tunnel Sensitivity to Flooding

To protect the integrity of the infrastructure, some tunnels physically close during extreme flooding using either gates or inflatable stoppers.

Source: Sandia National Laboratories (2011).

Valuation. VDOT suggests using an estimate of $20/ft^2 (FY2000) for constructing tunnels.[62] The methodology for converting this estimate to today's dollars and for estimating valuation of existing tunnels follows that described in the valuation section of roads.

This analysis found additional valuation information for tunnels considering costs of past projects. The original Chesapeake Bay Bridge Tunnel cost $200 million to build in 1960.[63] The parallel crossing that opened in 1991 cost $197,185,777.[64] In 1957, the $44 million Hampton Roads Bridge Tunnel opened. A parallel crossing for the HRBT opened in 1976 at the cost of $95 million. The HRBT was rehabilitated (shoulders were widened, a new bridge deck was built) for $34.7 million in 1999.[65] The MMMBT, built in 1992, cost $400 million.[66]

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[61] HRTPO (2012b).
[62] VDOT (2015a).
[63] Note: Dollar values have not been adjusted for inflation.
[64] Chesapeake Bay Bridge and Tunnel Commission (2014).
[65] Kozel (2007).
[66] Kozel (2004).

Railroads

Ownership and Inventory. According to the 2015 Railway Network from the National Transportation Atlas Database, there are approximately 532 miles of rail corridor and close to 600 miles of track in HR (see Table 20). Suffolk has the greatest number of rail infrastructure with 130 miles of rail, followed by Chesapeake with 76 miles.

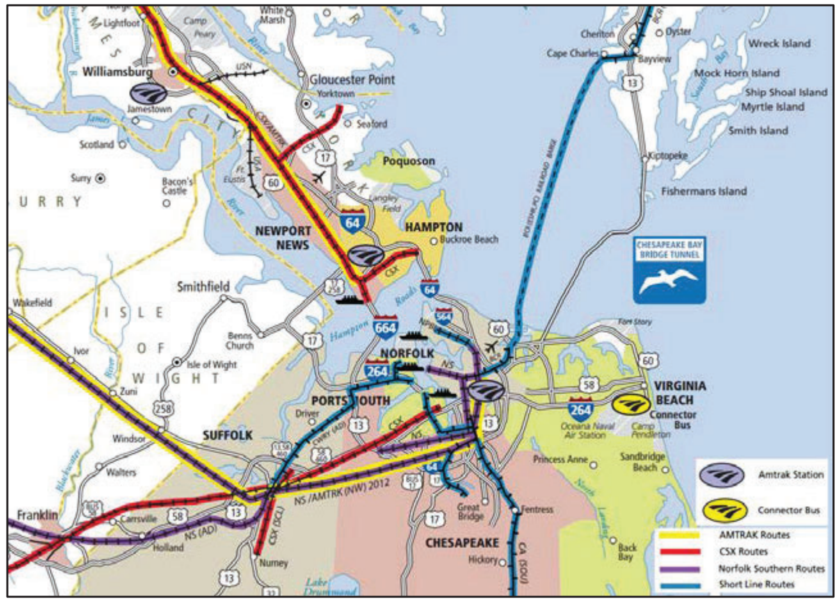

Figure 9. Hampton Roads rail lines (Source: VA Department of Rails and Public Transit (DRPT) (2012))

Table 20. Railway Network in HR (Source: NTAD)

CITY/COUNTY	MILES OF RAIL CORRIDOR	MILES OF TRACK	CITY/COUNTY	MILES OF RAIL CORRIDOR	MILES OF TRACK
GLOUCESTER COUNTY	-	-	HAMPTON	11.0	11.0
ISLE OF WIGHT COUNTU	30.8	40.0	NEWPORT NEWS	48.6	58.7
JAMES CITY COUNTY	18.2	26.5	NORFOLK	65.2	85.0
MATTHEWS COUNTY	-	-	POQUOSON	-	-
SOUTHAMPTON COUNTY	81.1	89.4	PORTSMOUTH	23.8	23.8
SURRY COUNTY	-	-	SUFFOLK	130.2	133.3
YORK COUNTY	12.0	14.4	VIRGINIA BEACH	35.0	35.0
CHESAPEAKE	75.7	87.3	WILLIAMSBURG	5.0	5.0
FRANKLIN	4.0	4.0			
TOTAL	**532.3**	**598.5**			

As shown by Table 21,

Table 21 CSX Transportation and Norfolk Southern are the two largest railroads owners in the Hampton Roads region. CSX owns 23% of rail corridors by mileage, and 24% of the track by mileage. Norfolk Southern owns 31% of the rail corridor and 35% of the track. A combination of other owners account for the remaining 45% of corridor and 41% of track. For location purposes, VDOT provides shapefiles of the spatial extent and location of rail assets in HR.

Table 21. Railroad ownership in HR (Source: NTAD)

OWNER	MILES OF RAIL CORRIDOR	% OF RAIL CORRIDOR	MILES OF TRACK	% OF TRACK
CSX TRANSPORTATION	124.6	23.41	145.8	24.36
NORFOLK SOUTHERN	166.4	31.26	208.6	34.85
OTHER	241.3	45.3	244.2	40.8
TOTAL	**532.3**	-	**598.5**	-

For the Norfolk area, there are 57 miles of rail corridor, and a total of 68 miles of track.[67] Table 22 shows the total length of the railway network. The Tide is a light-rail service with 7.4-miles of track in downtown Norfolk, as described in the Transit Section. Figure 10 illustrates the locations of rail lines in and around Norfolk.

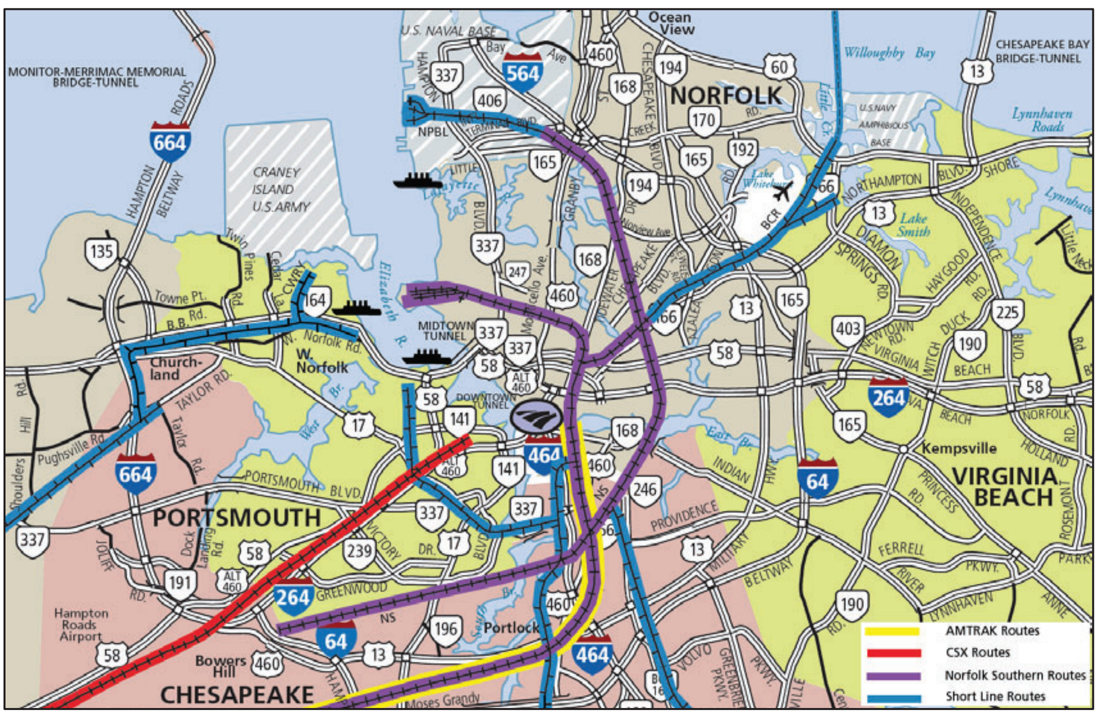

Figure 10. Hampton Roads rail lines; Southside Hampton Roads rail lines (Norfolk & vicinity) (Source: VA Department of Rails and Public Transit (DRPT) (2012))

[67]National Transportation Atlas Database (2015) .

Table 22: Railway network in Norfolk (Sources: NTAD and Norfolk OpenGIS)[68]

RAIL NETWORK	MILES OF RAIL CORRIDOR	MILES OF TRACK
PASSENGER RAIL (AMTRAK)	1.0	2.0
LIGHT RAIL	7.4	14.8*
FREIGHT RAIL	56.8	68.2**

**Includes both eastbound and westbound tracks. **Includes freight rail sidings.*

Use. During FY 2015, there were a total of 160,292 AMTRAK boardings and alightings in HR, which is about 10 percent of the total for Virginia.[69] In 2015, AMTRAK recorded 115,440 boardings and alightings in Newport News, 61,625 boardings and alightings in Williamsburg, and 44,852 boardings and alightings in Norfolk.

Condition. This analysis did not uncover data/information regarding the condition of rails.

Valuation. Data on valuation of rail track assets in Norfolk, obtained from the HAZUS-MH database for 93.8 mile of rail, suggest a total direct replacement cost for the Norfolk rail network at $83,428,000, in nominal dollars (with no information on the date of the estimate).[70] The range of cost estimates per track type, per kilometer, is between $1.5M for a regular segment of railway track to $10M for railway tunnels.[71]

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[68] Norfolk, City of, *Open GIS*, "Light Rail."http://data.orf.opendata.arcgis.com/datasets/54ed990ea6ba42a9b6940d5913692edf_0.
[69] AMTRAK (2015).
[70] Appendix D shows the HAZUS-MH cost estimates for specific components of the rail network.
[71] The HAZUS-MH database contains data on 93.8 miles of rail tracks for Norfolk, 8.8 miles greater than the total in the 2015 National Transportation Atlas Database (NTAD). One potential reason for the discrepancy is the fact that HAZUS-MH uses data from the 2001 version of NTAD, and perhaps reflects rail tracks that have since been removed from service. The HAZUS-MH helpdesk reports these estimates are dated, and no other information is available about more recent rail track costs.

Airports

Ownership and Inventory. Virginia has a total of nine primary commercial airports, as well as a number of military airports. Norfolk International Airport (ORF), a Federal Aviation Administration (FAA) National Plan of Integrated Airport Systems (NPIAS) classified as a small/non-hub airport with a significant military usage, is located in a densely populated area adjacent to the Chesapeake Bay (see Figure 11).[72] Norfolk International Airport is owned by the City of Norfolk with operations run by the Norfolk Airport Authority. Chambers Field (NAS) is owned and operated by the Navy.

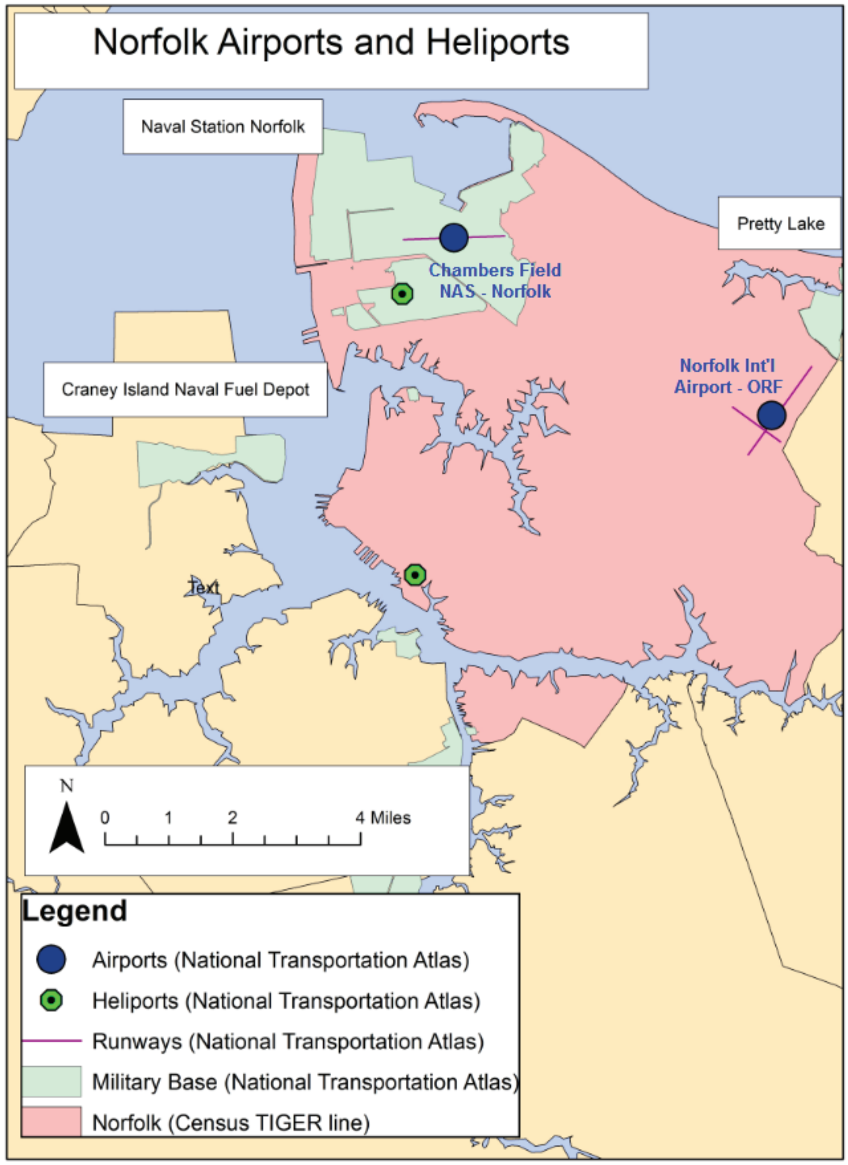

Figure 11. Norfolk Airports and Heliports (Source: NTAD)

Use. The nine primary commercial airports in the Commonwealth of Virginia experienced total enplanements of 24,480,117 in 2013.[73] For 2014, the FAA National Plan of Integrated Airport Systems (NPIAS) database indicates total enplanements of 24,467,633.[74] Airport traffic at Virginia's top four airports, with total enplanements of 23.6M, account for over 96 percent of total aviation traffic within the Commonwealth (see Table 23). Enplanements for ORF since 2004 have risen from 1.25 million in 2004 to a peak of 1.81 million in 2007, stabilizing round 1.6 million in 2013.[75] Usage data is not available for NAS because it is a military facility.

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[72] The remaining five smaller airports are Roanoke Regional (ROA), (310K); Newport News (PHF), (264K); Charlottesville (CHO), (231K); Lynchburg Regional (LYH), (78K); and Shenandoah Valley Regional (SHD), (20K).
[73] Old Dominion University (ODU) (2015).
[74] 2014 data may be obtained from the *National Plan of Integrated Airport Systems (NPIAS) Report.* FAA. See: http://www.faa.gov/airports/planning_capacity/npias/reports.
[75] See above reference for obtaining 2014 NPIAS data.

Table 23. Enplanements at Virginia's four busiest airports (Source: VA Chamber Foundation (2015))

AIRPORT	ENPLANEMENTS IN 2013 (MILLIONS)
WASHINGTON DULLES AIRPORT (IAD)	10.6
REAGAN NATIONAL INTERNATIONAL AIRPORT (DCA)	9.8
RICHMOND/HIGHLAND SPRINGS AIRPORT (RIC)	1.6
NORFOLK INTERNATIONAL AIRPORT (ORF)	**1.6**
TOTAL ENPLANEMENTS (IAD, DCA, RIC, ORF)	**23.6**
OTHER AIRPORTS	0.9
TOTAL VA ENPLANEMENTS	24.5

Operations are also significant measures on airport performance. FAA defines "Total Enplanement" as "revenue passenger boarding," while "Total Operations" refers to the number of take-offs and landings at that airport. Table 24 shows Total Operations for ORF, IAS, DCA and RIC for 2014 from the FAA Air Traffic Activity Data System (ATADS).

Table 24. ATADS-reported 2014 airport operations for ORF, IAS, DCA and RIC (Source: FAA ATADS)

FACILITY	ITERANT					LOCAL			TOTAL OPERATION
	Air Carrier	**Air Taxi**	**General Aviation**	**Military**	**Total**	**Civil**	**Military**	**Total**	
DCA	204,586	75,976	3,805	3,055	287,422	0	0	0	287,422
IAD	152,850	121,955	39,113	594	314,512	0	0	0	314,512
ORF	**26,126**	**25,483**	**18,182**	**1,010**	**70,801**	**3,905**	**141**	**4,046**	**74,847**
RIC	32,390	33,006	23,571	4,351	93,318	5,322	2,162	7,484	100,802
PHF	1,738	12,607	22,180	7,010	43,535	28,093	11,808	39,901	83,436

Condition. This analysis did not uncover data/information regarding the condition of airports.

Valuation. A study conducted in 2011 for the Virginia Department of Aviation on the economic performance of the nine Virginia commercial airports estimated the total economic impact of aviation for the commonwealth to be $20B. The report showed Norfolk's ORF to have total statewide economic impact of approximately $1B.[76]

This is similar to another study that estimated the ORF's total economic impact—direct, indirect, and induced impacts—at $1.36 billion.[77] The study noted that while the airport's direct contribution to the regional economy was relatively small, the indirect and induced impacts in terms of the multiplier effects of non-airport jobs and revenues with the supply chain have generated significant benefits for the entire HR region:

[76] Virginia Department of Aviation (2011)
[77] Norfolk Airport Authority (2007)

- *Direct economic impacts* accounted for roughly $136M (10 percent) of the economic impact, generated from passenger and cargo airline revenues, airport services and purchases;[78]
- *Indirect economic impacts* accounted for roughly $567M (42 percent) of the economic impact, generated by revenues and spending in supporting sectors not directly related to the airport;
- The *induced economic impacts* accounted for roughly $655M (48 percent) of the economic impact, revenues and incomes that are generated as the multiplier effect of the airport operations. The report indicated that these induced multiplier benefits of the airport are spread through the total regional economy, but primarily in Chesapeake, Portsmouth, Virginia Beach and Norfolk.

Sea Ports and Waterways

Ownership and Inventory. Port of Virginia (POV) is the gateway for waterborne cargo flowing through the region. Within this region there are state-owned and privately-owned terminals. State-owned or operated facilities are managed by the Virginia Port Authority, which owns or leases the region's four container cargo facilities: Norfolk International Terminal (NIT); Virginia International Gateway Terminals (VIG) and Portsmouth Marine Terminal (PMT) in Portsmouth, and Richmond Marine Terminal (RMT) in Richmond; and Newport News Marine Terminal (NNMT), a breakbulk and roll-on/roll-off terminal in Newport News.. The Virginia Port Authority created the Virginia International Terminals, a private non-profit organization, which is the operating arm that oversees daily operations.[79] In addition to these terminals, there are a number of privately owned marine terminals critical to the region's cargo movement.

These ports are responsible for the movement of a variety of goods. About 65 percent of deep draft ships call at the container terminals, 15 percent carry export coal moved through the coal terminals, and 20 percent call other private bulk terminals.[80] Bulk commodities may include the export of soy, grains, and wood chip products and the import of petroleum and fertilizers, among other goods.[81]

Use. In 2014, POV ranked as the 5th largest port in the US by container volume,[82] with peak season from August to November (which overlaps with hurricane season).[83]

NIT, VIG, and NNMT form the port's hub (see Figure 12). Deep channels, frequent weekly ocean-going vessel schedules, an efficient set of inland intermodal container transportation alternatives, and beneficial Foreign Trade Zone (FTZ) options combine to boost the HR port business. The Economic Impacts of the Virginia

[78] It should be emphasized that the ORF study was conducted in 2004, thus reflecting the lingering slowdown in air travel in the aftermath of the September 11, 2001 events.
[79] Old Dominium University (2015). Virginia International Terminals was established as a private nonprofit to allow for negotiations of contracts with unionized labor.
[80] Per interview with David White at the Virginia Maritime Association (8/8/2016).
[81] Per interview with David White at the Virginia Maritime Association (8/8/2016).
[82] Virginia Maritime Association (2016b).
[83] Per interview with David White at the Virginia Maritime Association (8/8/2016).

Maritime Industry report shows that the Virginia ports handled 78.9 million tons of domestic and foreign cargo in FY 2013, with an estimated value of $75.4 billion.[84] Below is a snapshot of the POV cargo movement profile:[85]

- *The Norfolk International Terminal (NIT*) container port operates on 378 of its total 567 acres with 14 Super Post Panamax ship-to-shore cranes with capacity to move 820,000 containers, equivalent to 1,426,800 Twenty-foot Equivalent Units (TEUs).

- *Virginia International Gateway Terminal (VIG)* in Portsmouth is privately owned, but operated by POV. It is a highly automated container terminal operating on 231 acres of a 576-acre tract. VIG has eight Super Post Panamax cranes with capacity to handle 650,000 containers (1,131,000 TEUs).

- *Newport News Marine Terminal (NNMT),* located on 165 acres north of the James River is POV's main breakbulk and roll-on/roll-off container facility.

- *Portsmouth Marine Terminal (PMT),* located on 287 acres along the Elizabeth River, did not have any operations in 2011, with studies underway for alternative future uses of PMT.

Both NIT and VIG have 50-foot-deep channels, making them well positioned to accommodate super containerships that are coming on line with the expansion of the Panama Canal. With a combined capacity of 2,557,800 TEU, the two ports in 2013 handled 2,165,435 TEU, or 85 percent of their total capacity. In 2014, the Mason School study reports a 6.5 percent growth for the ports, with a record container activity of 2,305,911 TEU, equal to 90 percent of the combined NIT and VIG container capacity. POV does not handle bulk coal cargo; all bulk coal moves are handled by private HR terminals.[86]

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[84] Virginia Maritime Association (2016a).
[85] College of William & Mary (2014).
[86] HR coal ports include: Lambert's Point/Pier 6, in Norfolk (owned by Norfolk Southern); Pier IX, in Newport News (owned and operated by Kinder Morgan), and; Dominion Terminal Associates, in Newport News (owned by Arch Coal, Peabody Energy and Alpha Natural Resources). Source: Platts (2016).

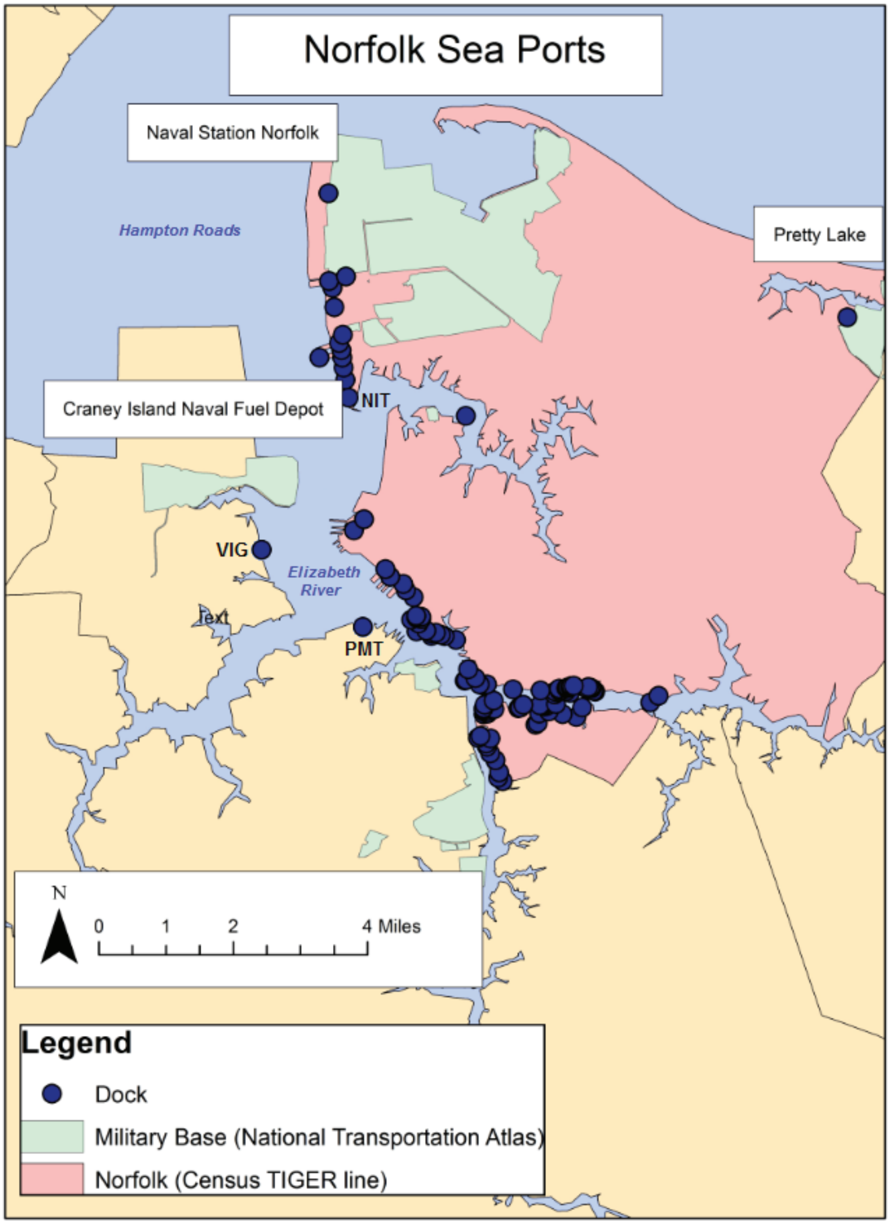

Figure 12. Norfolk Seaports (Source: National Transportation Atlas Database (NTAD))

A key measure of port activity is the volume of cargo containers moved by export or import vessels in domestic and international trade. Trucks carry 63 percent of the volume (778,316 TEUs), with the remaining balance carried by rail (410,947 TEUs, or 33 percent) and barge (53,514 TEUs, or 4 percent).[87] In the past few years, data on record growth rates in both POV tonnage and TEU movements suggest that POV has been one of the fastest-growing ports on the East Coast. In calendar year 2012, cargo tonnage grew to 17.53M tons (a

[87] Hampton Roads Partnership (2013).

12.2 percent tonnage growth); while TEU volume grew 10 percent in FY 2013, reaching a record volume of 2,165,435 TEUs.[88] Figure 13 shows the TEU container volumes by mode for the 2012-2013 time period.

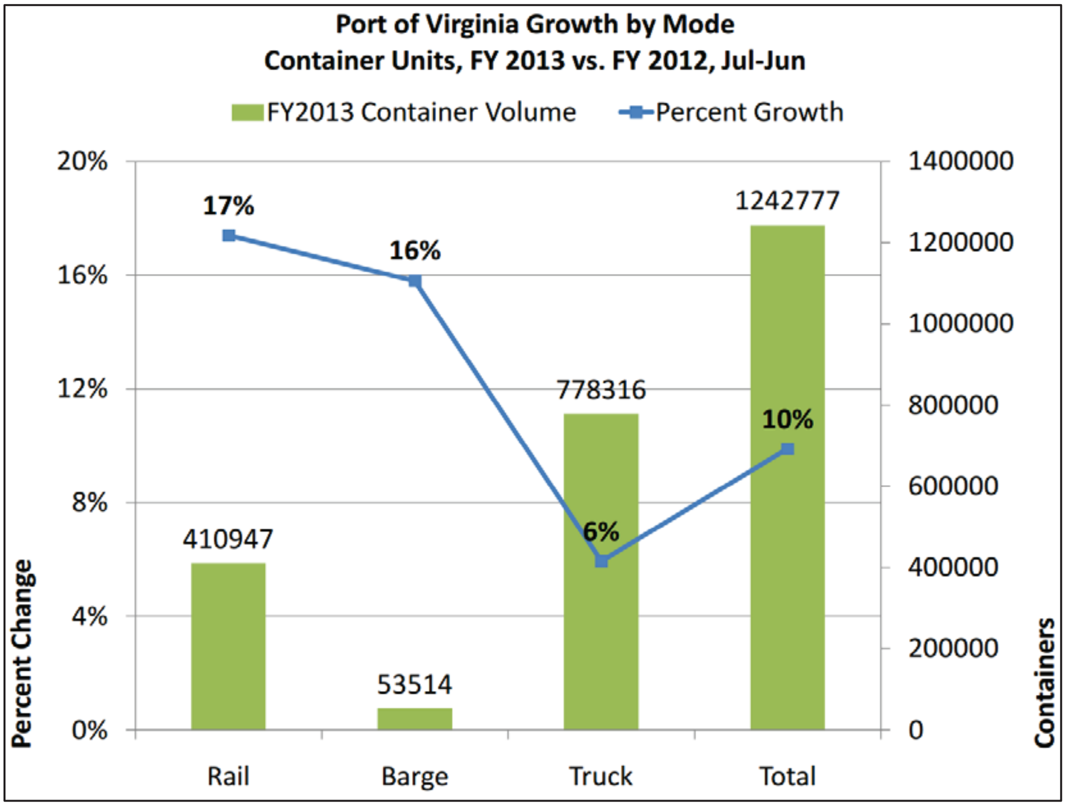

Figure 13. Port of Virginia Growth by Mode (Source: Hampton Roads Partnership (2013))

Even if a port is not directly impacted during and after a storm event, the transport of cargo to/from the port can be. For example, recent storms experienced in HR reduced the use of local roadways affecting cargo movement. Short 1-2 day disruptions due to extreme events are not likely to severely affect bulk facilities but may impact container operations. During peak season, there is less ability for a port to hold cargo on land if it's unable to move off the terminals which could also disrupt ship operations and sailing schedules. To improve operations and increase terminal cargo capacity, the Virginia Port Authority is beginning a $350 million expansion at NIT South to add 400,000 container capacity that will be completed in 2019. In addition, NIT will undergo a major expansion of gate facilities to allow more container access to highway travel.[89]

Condition. This analysis was not able to locate recent information regarding the condition of the ports; however, information from a 2001 workshop was available. In 2001, the U.S. Coast Guard (USCG) conducted a

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[88] Hampton Roads Partnership (2013).
[89] Per interview with David White at the Virginia Maritime Association (8/8/2016).

Ports and Waterways Safety Assessment (PAWSA) workshop about Hampton Roads.[90] A group of users and stakeholders evaluated waterway risks in HR. They rated various conditions on a scale of 1 to 9, with 1 being the best possible condition, and 9 being the worst.

Table 25 shows the ratings of various conditions. All were considered acceptable levels of risk, except for Waterway Complexity. The workshop called for improved communications in that area. Waterway Complexity was rated 8.3 because Hampton Roads has many intersecting channels, which leads to crossing traffic. There are also major bends in channels, which reduces visibility.

Table 25. Stakeholder ratings of risk for navigational conditions by risk factor (Source: USCG (2001))

RISK FACTOR	RATING	RISK FACTOR	RATING
NAVIGATIONAL CONDITIONS		**WATERWAY CONFIGURATION**	
WIND CONDITIONS	2.7	VISIBILITY OBSTRUCTIONS	3.7
VISIBILITY CONDITIONS	2.2	CHANNEL WIDTH	3.1
		BOTTOM TYPE	3.9
TIDE AND RIVER CURRENTS	3.8	WATERWAY COMPLEXITY	8.3
ICE CONDITIONS	1.9		

Dredging

Dredging is the act of removing sediment and debris from the bottom of waterways. It is used to both maintain and deepen channels. Sediment from rivers and storms settles on the bottom of waterways and must be removed or else channels will become shallower. Dredging can be an important strategy when considering preparation/responses to flood events.

United States Army Corps of Engineers (USACE) projects in HR waterways.[i]

Project	Description	Costs [ii]
Collection and Removal of Drift	▪ Remove hazards from navigation channel ▪ Five days a week	$998,000
Prevention of Obstructive and Injurious Deposits	▪ Surveillance and supervision operations	$72,000
Deepening	▪ Reconnaissance report on Elizabeth River 45 ft and Southern Branch 40 ft project ▪ Update navigation management plan for HR	$113,000
Maintenance	▪ Dredged Norfolk Harbor Reach and Craney Island Reach to minimum safe level ▪ Maintain critical dike at Craney Island	$8,060,000

[i] USACE (2011).
[ii] Cost is in 2012 dollars.

[90] USCG (2001).

Valuation. Virginia's non-military maritime industry plays a large role in the Commonwealth's economy. In FY 2013, 78.9 million tons of cargo valued at $75.4 billion were moved through Virginia's ports. 16.9 million tons, valued at $18.3 billion, were made in Virginia. 6.7 million tons stayed in Virginia, and created $24.9 billion in spending for goods and services.[91] These figures are for Virginia with HR representing a significant portion of these numbers.[92] The report analyzed six ports: Norfolk, Portsmouth, Chesapeake, Newport News, Richmond, and the Virginia Inland Port in Front Royal. Four of these (Norfolk, Portsmouth, Chesapeake, and Newport News) are in the HR region.

According to a recent report on the economic impacts of POV,[93] in 2013, POV moved 18 million tons of cargo valued at $53.2B; 4.5 M tons of made-in Virginia exports valued at $10.9B; and 3M tons of imported goods that are retained in VA as inputs for commercial production and local consumption valued at $10.4B. Table 26 and Table 27 show the components of the POV impacts on the regional economy and its contribution to the Gross State Product (GSP).

Table 26. Components of POV's Contribution to the Regional Economy (Source: College of William & Mary (2014))

COMPONENTS OF THE POV PORT OPERATIONS	POV SPENDING ($M)	POV VALUE-ADDED (GSP) ($M)	POV EMPLOYEE COMPENSATION ($M)	POV EMPLOYMENT
SHIP & HARBOR OPS, VESSEL LOADING/UNLOADING	$980	$409	$309	3,900
WAREHOUSE/STORAGE	$115	$69	$65	1,412
FREIGHT SERVICE SUPPORT	$435	$189	$187	3,815
TRUCK AND RAIL TRANSPORT	$934	$446	$302	5,001
TOTAL	**$2,464**	**$1,113**	**$862**	**14,128**

Table 27. Total economic impacts of the POV disaggregated by direct, indirect, and induced impacts (Source: College of William & Mary (2014))

COMPONENTS OF POV PORT OPERATIONS IMPACTS	DIRECT ($M)	INDIRECT ($M)	INDUCED ($M)	TOTAL ($M)
REVENUES/SALES	$2, 464	$1,041	$1,721	$5,226
VALUE ADDED (GSP)	$1,113	$645	$1,087	$2,846
EMPLOYEE COMPENSATION	$862	$481	$588	$1,931
TOTAL	**$4, 439**	**$2,167**	**$3,396**	**$10,003**

Putting the economic impact of the POV in the context of the total economy of the Commonwealth, the FY2013 Mason School report on POV estimated the total contribution of POV to the regional economy at $30.5B, or 6.8 percent of the Commonwealth's $448.8B GSP, partly due to the high percentage of the region-

[91] Virginia Maritime Association (2016a).
[92] Per interview with David White at the Virginia Maritime Association (8/8/2016).
[93] College of William & Mary (2014).

wide economic impacts of the port that is generated in HR.[94] Similarly, HR's total employee compensation of $17.5B was calculated at 9.4 percent of VA total employee compensation.

POV's contribution to regional export/import economy is also significant. POV exports some 1.3M tons of export cargo with their production origin in HR. The region's exporters shipped 116,989 container TEUs with a value of $3.2 B. All these tonnage and cargo values accounted for about 29 percent of the Virginia-made export goods. Imports into the HR ports accounted for a lower share of both the volume and value of the Virginia trade activities: HR ports imported 812,961 tons of cargo, valued at $2.6B, accounting for 27.5 percent of the Virginia-used tonnage, and 25.3 percent of its value.[95]

Table 28 shows the percentage distribution of the components of the economic impacts of spending, regional value-added, and employee compensation. The table indicates that the relatively low value-added for the port-related activities stems largely from the fact that although a high amount of cargo handling is done on the imports in HR, the imports have a relatively low overall share in the total regional economy because the value-added from the price markups is low, given the small share of the imports being consumed in HR.

Table 28. Economic impacts of port trade in HR, by economic activity and impact type (Source: College of William & Mary (2014))

ECONOMIC IMPACTS OF PORT TRADE IN HR	DIRECT	INDIRECT	INDUCED	TOTAL IMPACT
SPENDING	30%	21%	36%	29%
VALUE-ADDED	12%	14%	20%	14%
EMPLOYEE COMPENSATION	21%	22%	36%	25%

Another source of asset valuation for the region's port-related assets is the HAZUS-MH database's asset records for 91 port facilities in Norfolk, indicating a combined port-asset valuation of $181,727,000. These HAZUS-MH data on HR seaports provide an inventory of port traffic and asset valuation for waterfront structures, cranes, cargo handling equipment, warehouses, and fuel facilities. HAZUS-MH also contains records of three ferry facilities, with a combined valuation of $3,993,000. The HAZUS-MH port database was developed from the calendar-year 2000 database of Port and Waterway Facilities, maintained by the U.S. Army Corps of Engineers (USACE) Institute for Water Resources Navigation Data Center (Ports and Waterways Division). The 2015 version of the USACE database includes 117 port facilities, representing an increase of 26 port facilities from the 2000 HAZUS-MH data. This suggests that new port facilities may have been added in the intervening 15 years. As with the down-side bias in estimated values of the regional bridge and rail assets, the above HAZUS-MH valuation of the POV is likely to be understated.

[94] The sources of data for the POV report were data from the Bureau of Economic Analysis (BEA) sectoral output that were used to calculate the total contribution of the HR Metropolitan Statistical Area (MSA) and POV to the regional economy.
[95] Data sources for these estimates included data from PIERS (Port Import Export Reporting Service) – with data on tonnage, TEU, origin-destination, and harmonized commodity codes – and other DOC International Trade Administration (ITA), BEA, and Census Bureau databases.

Pipelines

Ownership and Inventory. Historically, natural gas consumed in Hampton Roads has been transported by two primary interstate pipelines: Columbia Gas transmission feeding South Hampton Roads, and Virginia Natural Gas (VNG) supplying North Hampton Roads. Local distribution within Norfolk and most of HR itself is provided by VNG. [96] Figure 14 shows pipeline assets of Columbia (in green) and VNG (in blue and red) serving HR.

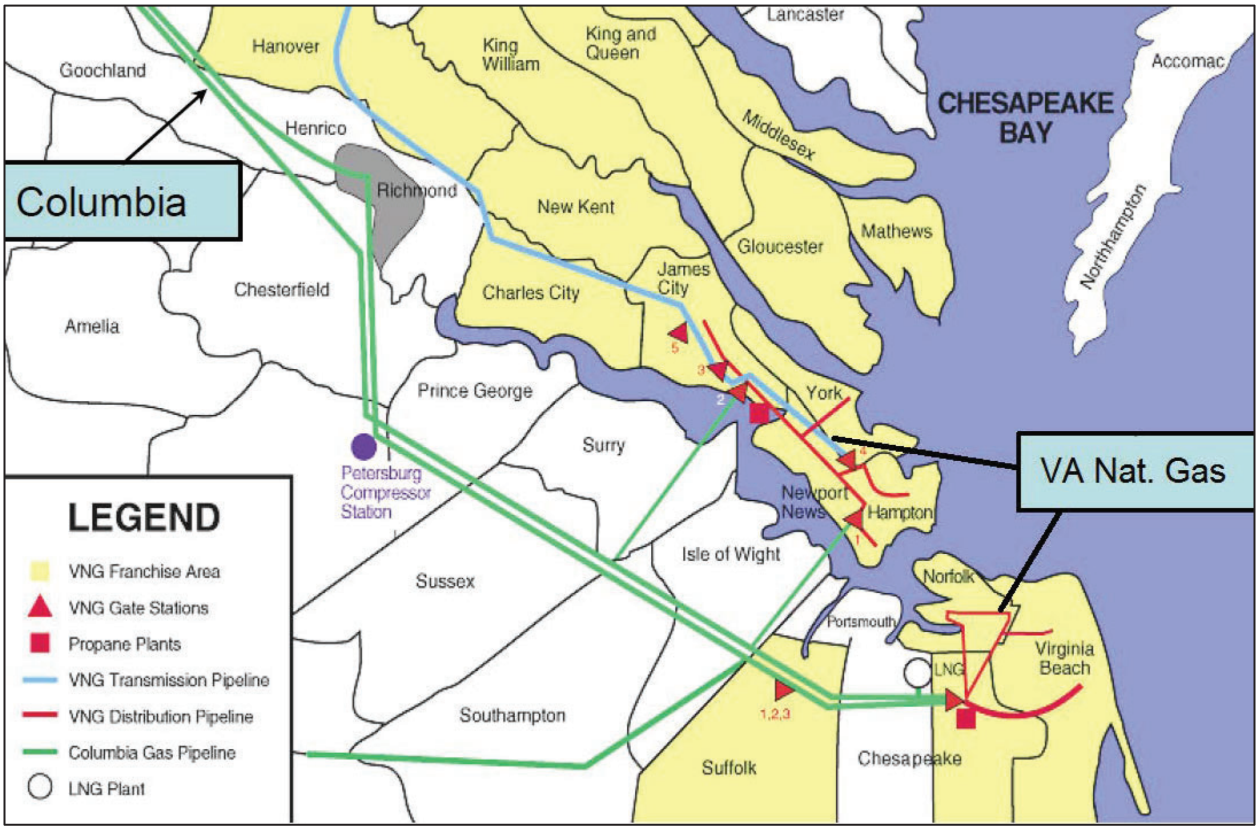

Figure 14. HR pipeline infrastructure (Source: Virginia Natural Gas)

Use. The geographic division created by the HR waterbody and resultant two non-contiguous gas distribution systems (Northern and Southern)[97] exposed HR to natural gas supply and price vulnerabilities. This is because on any peak day, each system was fed by a single interstate pipeline (VNG in the North, Columbia in the South).[98] Until recently, because South HR was only served by one major pipeline, Norfolk and neighboring municipalities had grown dependent on back-up systems (especially on the coldest heating days) fueled by propane and/or liquefied natural gas (LNG) transported in by truck.

[96] Virginia Department of Mines, Minerals and Energy (2014).
[97] The Southern system includes the areas of Norfolk, Virginia Beach, Chesapeake and Suffolk in south side Hampton Roads. The Northern system includes Hampton, Newport News, Poquoson, York, James City, Williamsburg, New Kent, and Charles City on the Peninsula, as well as Hanover and King William counties.
[98] Virginia Natural Gas (n.d.).

To address this supply constraint, VNG developed the Hampton Roads Crossing (HRX) pipeline project to connect the two Northern and Southern HR gas distribution systems by way of a new pipeline water crossing across HR Harbor (Figure 15).

Figure 15. HRX pipeline (Source: Virginia Natural Gas)

The HRX pipeline was completed in 2010, providing substantial gas supply and reliability benefits to residential and business sectors in the HR region, as well as ensuring a more stable gas supply to military facilities in the Southern distribution system including Norfolk Naval Station, Oceana Naval Air Station, Little Creek Amphibious Base, Dam Neck Naval Training Station and Fort Story. The HRX pipeline and associated compressing equipment has also provided increased gas access to some of Dominion Virginia Power's gas-fired electric generating plants in central Virginia. The HRX has also opened up HR's access to a broader

geographical range of natural gas supplies, including the Marcellus Shale, Rockies, Mid-Continent, Gulf Coast and other locations (see Table 29 for additional description of the HRX pipeline).[99]

Table 29. Description of the Hampton Roads Crossing (HRX) Pipeline (Source: Virginia Natural Gas website)

HAMPTON ROADS CROSSING (HRX) PIPELINE	
COMMISSIONED:	The Hampton Roads Crossing (HRX) Pipeline was completed and put into service in 2010.
OWNER/OPERATOR:	Virginia Natural Gas
CONNECTS:	Connects gas distribution systems in Northern Hampton Roads (Newport News, Hampton) and Southern Hampton Roads (Norfolk, Portsmouth, Virginia Beach).
LENGTH:	21-miles of 24in. pipe: • 7 miles in Hampton/Newport News • 4 miles in Norfolk • 10 miles of water and island crossing ○ 4 mile harbor crossing ○ 4.5 miles on Craney Island ○ 1.5 mile Elizabeth River crossing
CAPACITY:	Over 100,000 dekatherms natural gas per day

Condition. This analysis was not able to locate recent information regarding the condition of the pipeline.

Valuation. This analysis was not able to locate recent information regarding the valuation of the pipeline.

1-1-2 Service Operations

Freight Network: Trucking and Multi-modal Operations

Hampton Roads Transportation Planning Organization (HRTPO) conducted a study in 2012 on the HR regional freight.[100] The study identified the regional freight movement patterns and the commodity-flow data for all modes, including trucking, rail, and water. The source of the HRTPO's data for the region's freight movements was the Commodity Flow Survey (CFS) database used in the FHWA Freight Analysis Framework (FAF) data on Origin-Destination (O-D) freight movements by mode, weight, and value for existing (2010) and projected 2040 conditions. Table 30 summarizes the four freight transfer facilities in Norfolk. This report's Sea Ports and Waterways' section provides some data on freight container movement in the Port of Virginia. Further

[99] Virginia Natural Gas (n.d.).
[100] HRTPO (2012c).

information may be collected to analyze the economic value of the trucking and rail industry in HR for the transportation of goods and services.

Table 30. Freight facilities in Norfolk (Source: 2015 National Transportation Atlas Database)

NAME OF FREIGHT FACILITY	MODES
NORFOLK INTERNATIONAL AIRPORT	Air and truck
NORFOLK SOUTHERN BULK TRANSFER TERMINAL	Rail and truck
NORFOLK WAREHOUSE DISTRIBUTION CENTERS, INC.	Rail and truck
NORFOLK INTERNATIONAL TERMINALS	Port, rail, and truck

Transit

Hampton Roads Transit (HRT), currently serves the Southside and Peninsula areas of Hampton Roads, consisting of the cities of Hampton, Norfolk, Newport News, Portsmouth, Suffolk, Chesapeake, and Virginia Beach. Major HRT assets include a light rail transit system in downtown Norfolk (The Tide), an expansive bus service network, and ferry services.[101] The following details each of these:

Light Rail Transit (LRT) – The Tide

- The Tide light rail transit system opened its "starter line" in 2011.
- The current line includes 11 stations and extends 7.4 miles through downtown Norfolk (Figure 16).
- Operates 9 light rail transit vehicles.
- Averages over 1.65M passenger trips per year.[102]
- The majority of the line is ¼ mile or less from the waterfront; several stations lie within 800 ft from the water, including one less than 1/10 mi from the coastline. The light rail track itself crosses creeks and rivers in multiple locations.[103]
- HRT is examining alternatives analyses for potential extension of The Tide to Norfolk Naval Base, Old Dominion University, Norfolk International Airport, and Virginia Beach.

[101] HRT (n.d.)..
[102] HRT (2014).
[103] Analysis based on Google Earth imaging.

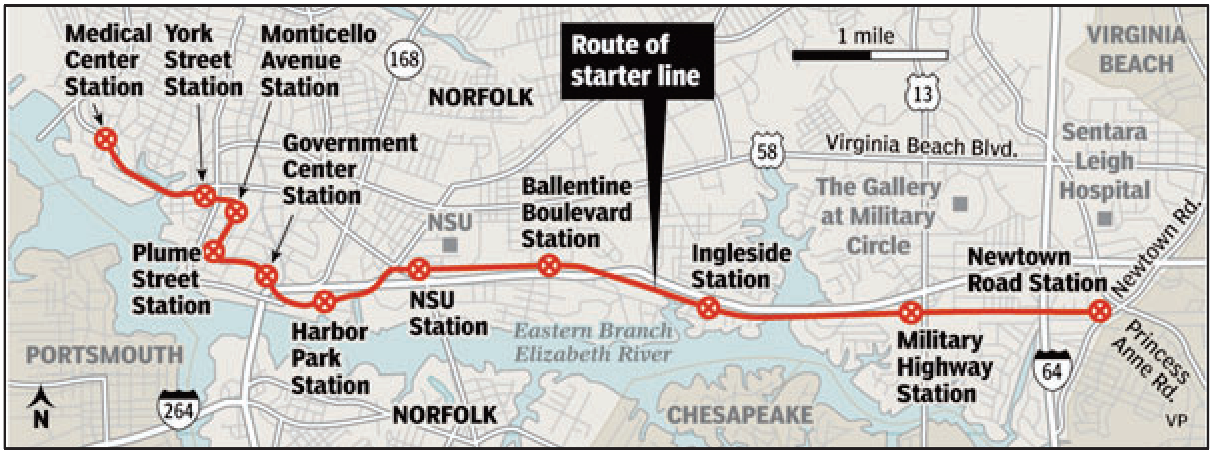

Figure 16. The Tide light rail system (Source: www.hamptonroads.com)

Bus Services

- Provided over 17.9 million passenger trips in FY14 to people in Chesapeake, Hampton, Norfolk, Newport News, Portsmouth and Virginia Beach. [104]
- Fleet includes 302 buses (255 diesel buses, 37 hybrid buses and 10 trolley-style buses).[105]
- 3,500 bus stops & 199 bus stop shelters.
- Includes six major transfer centers – four of which are within a ½ mile of the coast.[106]

Ferry Services

- Ridership typically averages ~350,000 ferry passenger trips per year.[107]
- Operates routes between Norfolk and Portsmouth on the Elizabeth River (Figure 17).
- Includes four ferry docks.
- Fleet includes three 150-passenger ferry vessels.
- Waterfront parking facility (Portsmouth).

[104] HRT (2014).
[105] As of August 2011.
[106] Analysis based on Google Earth imaging.
[107] HRT (2014).

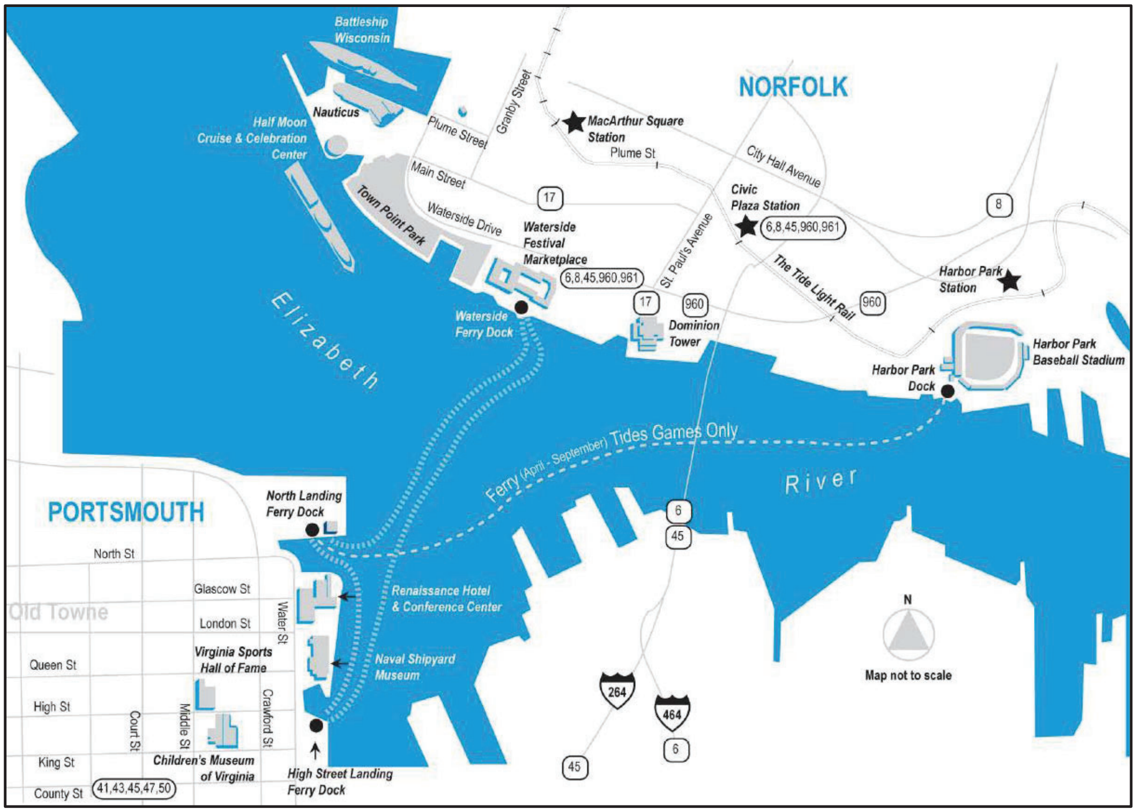

Figure 17. Hampton Roads Ferry Routes & Docks (Source: Hampton Roads Transit)

1-2 DATA FOR ANALYZING INDIRECT ECONOMIC IMPACTS ON THE MULTIMODAL TRANSPORTATION SYSTEM

To fully capture the extent of indirect losses associated with loss of transportation services or changes in the current transportation system in response to implementation of adaptive strategies, we need to quantify the climate-related losses associated with costs of business interruption, reduced access to critical infrastructure, social vulnerabilities arising from poverty and lack of transportation access, and associated with right-of-ways. To consider this, this section discusses HR (including Norfolk) economy, demographics, and critical infrastructure. In addition, right-of-way considerations and indices used to identify vulnerable populations are also introduced.

1-2-1 Economy

Employers. The region is home to 16 federal agencies, including numerous Department of Defense (DOD) installations and the world's largest naval station, Naval Station Norfolk. Figure 18 shows the percent of employment by industry in the Hampton Roads Metropolitan Statistical Area (MSA). In 2011, the military accounts for 9.4 percent of all employment in HR.[108]

[108] HRPDC (2013).

By sector, employment change in the 2009-2014 shows the best-performing sector to be Professional and Business Services at a growth rate of 28.36 percent; and the worst-performing sector the Information Sector at a rate of -30.13 percent.[109]

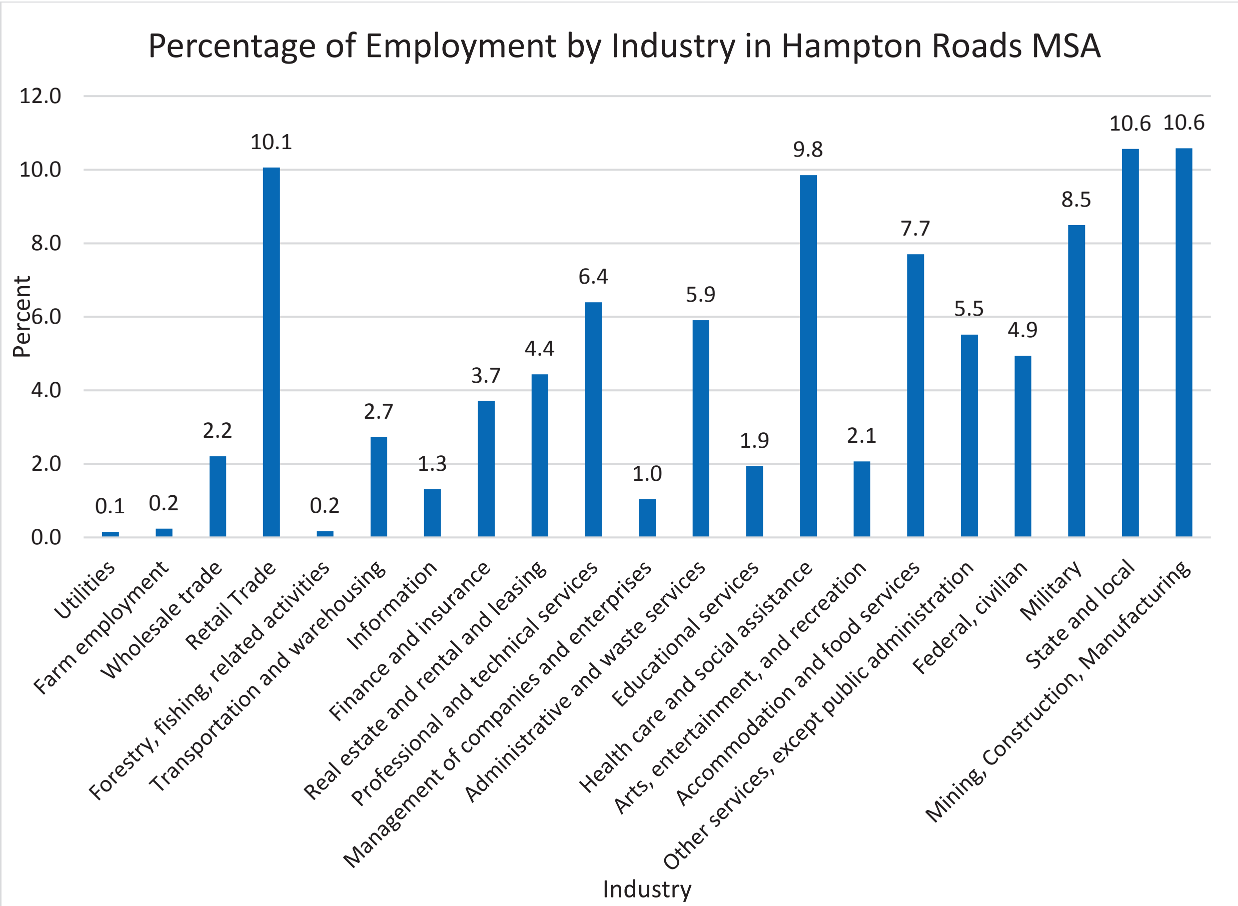

Figure 18. Percentage of employment by industry in Hampton Roads MSA for 2014 (Source: data from HRPDC's Hampton Roads Data Book: Employment)

Figure 19[110] shows the Norfolk share of HR employment by industry (comprising mostly around 10-15 percent of the employment in each sector), highlighting the significant share of military employment in HR is located in Norfolk (largely attributed to Naval Station Norfolk), accounting for close to a third of the employment.[111]

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[109] ODU (2015).
[110] HRPDC (n.d.).
[111] Sandia National Laboratories (2016).

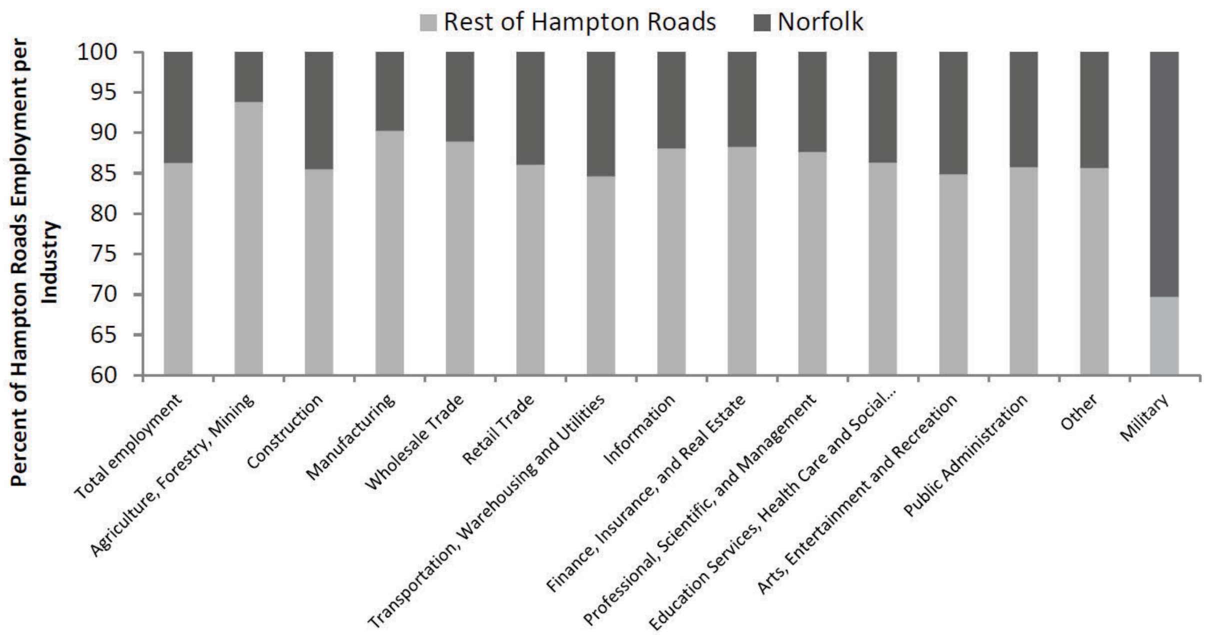

Figure 19. Norfolk share of total HR employment by industry (Source: data from Sandia National Laboratories (2016), U.S. Census Bureau)

With respect to the military's large share of the Norfolk economy, recent fluctuations in military budget and expenditures have substantially contributed to changes in Norfolk's employment levels. The significance of the defense industry in the economic stability of the HR region in general, and in Norfolk in particular, is further examined below.

Employment Rates. The HR region's total employment in 2013 was 720,000. Norfolk's employment of 136,300 comprises 19 percent of the region's total employment (compared to its population share of 14.6 percent). HR has experienced a lower rate of employment growth compared to the rest of Virginia (at near zero growth rate compared to 1.72 percent growth in Northern Virginia and 0.99 percent statewide), which has in part been attributed to its lower business startup rate.[112] This also corresponds to a regional slow-down in population growth, which is in large part due to the loss of population in Norfolk.[113]

Military. The military facilities located in HR and Norfolk are a key economic driver in the region and are highly vulnerable to coastal flooding and SLR threats. Table 31 lists employment data for six of the key DOD

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[112] Hampton Roads Partnership (2013) indicates an improving situation, with an increase in the number of startups per 10,000 residents from 5.0 in 2003 to 9.4 in 2012 (with a peak of 10.7 during the pre-recession year of 2007). The reports notes that HR has the second highest *Employment to Household Ratio* in VA (1.5), second after Northern VA (1.7). A jobs to housing ratio greater than 1 indicates that more jobs than housing exists within the jurisdiction; a ratio of 2:1 is typically promoted as an ideal balance that provides jobs and retail opportunities for all the population within the area (thus reducing the need to commute to outside the region for work).

[113] VTrans (2010). The report states that net migration in Norfolk (comprised of domestic and international migration) has declined or remained unchanged over the last decade.

facilities in or around Norfolk, reporting over 72,000 Active Duty personnel, almost 8,000 Reserves, almost 34,000 civilian employees, and over 13,000 contractors, amounting to a total direct employment of 127,022.

Table 31. Norfolk Area Military Facilities. (Source: Vanderley 2016)

NORFOLK AREA MILITARY FACILITIES	ACTIVE DUTY	RESERVES	CILIVIAN	CONTRACTOR
NAVAL STATION NORFOLK	42,997	1,462	13,468	7,037
JOINT EXPEDITIONARY BASE LITTLE CREEK-FORT STORY	10,422	4,547	3,222	723
NAVAL AIR STATION OCEANA/DAM NECK	9,724	980	2,786	3,080
NORFOLK NAVAL SHIPYARD	804	96	9,921	1,553
NAVAL WEAPONS STATION YORKTOWN	1,379	186	1,103	453
NAVAL SUPPORT ACTIVITY HAMPTON ROADS	6,942	445	3,266	456
TOTAL	**72,268**	**7,716**	**33,736**	**13,302**

Hampton Roads Planning District Commission (HRPDC) conducted an economic impact analysis to quantify the direct and indirect economic impacts of DOD employment in HR. The study team used the Regional Input-Output Model System (REMI) and Computable General Equilibrium (CGE) methodology to estimate the full economic impacts, direct and indirect employment impacts and contribution to the HR region's earnings and Gross Domestic Product (GDP), as summarized in Table 32 (see Part 2 of this report for model for description of REMI model and other I-O and CGE methodologies). The REMI model measured the significant multiplier effect of military employment in HR, as indicated by the model's estimate of an employment multiplier of 1.873 for the military sector. This multiplier of 1.873 means that for every 1,000 direct defense employees in HR, 873 indirect and induced jobs are created inside and outside the region.

Table 32. Economic Impact of Military Personnel in Hampton Roads (Source: HRPDC (2013))

MILITARY PERSONNEL IMPACT CATEGORY	TOTAL HAMPTON ROADS ECONOMIC IMPACT
DIRECT EMPLOYMENT	92,962
INDIRECT AND INDUCED EMPLOYMENT	81,200
TOTAL EMPLOYMENT	174,162
TOTAL EARNINGS IMPACT	$10.9 Billion
GROSS REGIONAL PRODUCT	$16.6 Billion

Another illustration of the extent of military economic impact in Norfolk is the Langley Air Force Base. In 2006, Langley's employment and spending profile was as follows: direct agency procurement and spending: $722M;

direct spending by visitors: $5.4M; indirect expenditures: $378M; induced expenditures: $1.2B. Total jobs created were 20,649 (direct: 7,529; indirect: 2,985; induced: 10,135).[114]

VDOT Roadway User Costs. VDOT has a methodology for calculating roadway user costs for delays to travelers in response to closing a road or other asset within the transportation system. Costs include such factors as lost wages and extra fuel consumption. This methodology has been adopted by HR. Further discussion is warranted to determine the availability and best use of this work in this study.[115]

1-2-2 Demographics

Income. According to the 2015 *State of the Commonwealth Report*[116] the median household income in 2013 in Norfolk was $44,747, compared to $62,666 for the Commonwealth of Virginia.[117] Table 33 compares median and real income levels (adjusted for cost-of-living) in Norfolk, the Commonwealth of Virginia, and the United States in 2013.

Table 33. Income and cost of living in 2013 for Norfolk, Commonwealth of Virginia, and the U.S. (Source: Old Dominion University (ODU) (2015); Norfolk, City of (2014))

LOCALITY	MEDIAN INCOME 2013	NUMBER OF HOUSEHOLDS	COST-OF-LIVING INDEX (COLI)	REAL MEDIAN INCOME, 2013
CITY OF NORFOLK	$44,747	85,557	112.9	$39,634
HAMPTON ROADS MSA*	$56,161	628,572		
COMMONWEALTH OF VIRGINIA	$63,907	3,055,863	103.2	$61,925
UNITED STATES	$53,046	116,291,033	100	$53,046

**Data for Hampton Roads is from the 2010 census*

In 2011, HR had the largest percentage of residents in Virginia with incomes below the federal poverty level.[118] The HR poverty rate was 12.4 percent, compared to the rate of 6.8 percent in Northern Virginia, and the overall VA rate of 11.5 percent.[119] In Norfolk the median household income is about $44,743, compared to about $52,000 for the Commonwealth as a whole. Only 45.4 percent of homes are owner-occupied in Norfolk, which is lower than the percentage of owner-occupied homes in the Virginia Beach—Norfolk—Newport News MSA (63.1 percent).[120]

The Norfolk-Virginia-Beach-Newport News MSA had a lower rate of GDP growth, 0.31 percent average annual growth from 2009 to 2014, compared to the Washington DC-Arlington-Alexandria-Maryland MSA, 1.00

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[114] NASA (2006).

[115] Per communication with John Mazur at FHWA.

[116] ODU (2015).

[117] The ODU report highlights the significance of applying the cost-of-living index (COLI) factor to arrive at real median income. It notes that in 2013 Virginia's real income in 2013 ($63k, with a relatively low COLI of 103) was far higher than high-income cities such as Manhattan, which has a nominal median income of $69k, but with a COLI of 185, a "real income" of just $38k. Similarly, for Brooklyn, NY, the nominal income was $46k; making the real income $24,500 after applying the COLI of 188.

[118] Hampton Roads Partnership (2013).

[119] The Hampton Roads Partnership (2013) reports that in 2011, HR had a per-capita income of $11,484 for an individual.

[120] Norfolk, City of (2014).

percent average annual growth.[121,122] Influencing the MSA salaries are the business cycle, the mix of industries, and other factors such as a slowdown in the growth of the defense industry. As noted above, HR is part of Norfolk–Virginia Beach-Newport News MSA. However most of the income statistics reported in the study are for Norfolk.

1-2-3 Critical Infrastructure Facilities

Further underscoring the difficulty of determining the extent of indirect costs of climate-related disruption is the intermingling of the private assets with the critical infrastructure facilities. The National Oceanic and Atmospheric Administration's (NOAA's) Coastal Economy Database for Norfolk contains information on 413 "critical facilities" located in Norfolk—schools, hospitals, fire stations, police departments, dams, and transportation infrastructure assets—that represent both asset vulnerability and also rank high on a prioritization scale when emergency conditions prevail. Table 34 lists these facilities that show the distinct public-goods character of many Norfolk critical infrastructure assets.

Table 34. Critical facilities in Norfolk (Source: NOAA Coastal Economy Website)

NORFOLK CRITICAL FACILITIES	FACILITY COUNT
MEDICAL FACILITIES	7
COMMUNICATION TOWERS	4
DAMS	1
EMERGENCY CENTERS	1
FIRE STATIONS	2
HAZARDOUS MATERIALS FACILITIES	28
HIGHWAY BRIDGES	173
POLICE STATIONS	11
PORT FACILITIES	91
POTABLE WATER FACILITIES	3
SCHOOLS	89
WASTEWATER FACILITIES	3

1-2-4 Right-of-Way Considerations

The term Right-of-way (ROW) is defined as "any real property, or interest therein, acquired, dedicated, or reserved for the construction, operation, and maintenance of a highway."[123] The acquisition of real property interests is a fairly typical activity that is required in order to construct many transportation projects, or

[121] In May 2015, the state unemployment rate was 4.5%, compared to the US average of 5.1%, showing a lower rate from the peak unemployment rate of 7.4% in 2010.
[122] ODU (2015).
[123] 23 U.S.C. (2012).

expand an existing transportation facility outside of the limits of its existing footprint. This activity must be taken into account early in the project planning process in order to ensure timely project delivery.

Depending on the impacts of a given project, the acquisition of all necessary real property rights (and the potential relocation of property owners and tenants) can become a major project cost. This applies to all Federal or Federally-assisted projects, including transportation projects associated with SLR and coastal flooding adaptation. This is also true for projects involving the expansion or relocation of ROWs for roads, bridges, or highways, and for impacts to access to existing uses, wetlands, and ROW-related stormwater management.

The acquiring agency must comply with all applicable provisions of 42 USC Ch. 61: Uniform Relocation Assistance and Real Property Acquisition Policies for Federal and Federally Assisted Programs ("Uniform Act" or "UA") whenever there is Federal funding participation in any phase of a public project. The acquisition of real property interests in connection with any Federal or Federally-assisted program or project must be carried out in accordance with the Uniform Act. This law is intended to provide for the uniform, fair and equitable treatment of persons whose real property is acquired or who are displaced in connection with Federally funded projects.

The goal should always be to acquire the necessary property rights through amicable negotiation, but realistically, most large or complex transportation projects involve the acquisition of at least some property rights through the power of eminent domain, via the condemnation process. All project cost estimates should include the projected acquisition cost of the necessary property rights (and possible condemnation costs) and the costs to relocate all displaced property owners, tenants and businesses.

It should also be noted that in addition to cost to acquire sufficient ROW for a project, an acquiring agency may be required to compensate some impacted property owners for "legally-compensable damages", occurring as a result of the project. Whenever the amount of damages is determined through the condemnation process, the level of financial risk is heightened and it is advisable to factor in that variable in some manner.

Very often, the realty or ROW impacts of a project will require the relocation of existing utilities such as water, sanitary sewer, power, cable, telephone and other utilities. Regardless of whether these are public or private utilities, their relocation must be coordinated with road/bridge/highway work.[124] There may also be indirect costs related to these other services that rely on the transportation network under an "as-is" condition. For example, if electrical infrastructure is buried underneath the roadway, widening or raising the roadway may result in additional maintenance costs to the electrical infrastructure.[125] These are indirect costs that are not generally considered in a traditional transportation economic analysis but can have significant impacts on the bottom line and operations for the utility industry. The transportation ROW-related costs in this regard are

[124] Per communications and comments from Henry R. ("Speaker") Pollard, V, a partner with the law firm of Williams Mullen and chair of its Coastal Flooding and Resiliency practice group.
[125] Per communication with Robert Martz, Hampton Roads Sanitation District (HRSD).

only part of the pending and growing infrastructure costs associated with already needed repairs, replacements and expansions for roads/bridges/highways, water supply and treatment systems, stormwater management systems, and wastewater/sanitary sewer collection and treatment systems.[126]

It should also be noted that the need to ensure sufficient ROW or accessibility is not limited to transportation agencies or utility providers. Some private property owners and even other governmental or institutional facility owners and operators seeking to plan for, adapt or defend against sea level rise and flooding impacts may over time need to expand their own property holdings or interests to install adaptive or defensive measures or otherwise improve the quality of their property's access. As a result, these landowners can be expected to face their own needs and challenges to secure or improve their own ROWs and site accessibility to ensure ingress and egress and otherwise to protect their property. These efforts may interconnect with, or perhaps even conflict with, transportation ROW projects. While such landowner needs and efforts may not be known with certainty at the outset, the identification and engagement of potentially-impacted stakeholders should be pursued as the project planning stage moves forward. Accurately forecasting the costs of such ROW considerations over a transportation project's useful life is no small task. To a great extent, such accuracy depends greatly on the accurate projection of sea level rise and coastal flooding impacts, as well as an accurate assessment of current and expected land uses. In turn, it is important for federal and other transportation agencies to coordinate closely with local and regional planning officials and to stay current with and utilize appropriate projections of such impacts early in the project planning process.[127]

1-2-5 Vulnerable Populations.

USDOT policy supports including inequality and environmental justice issues when evaluating climate change impacts and adaptation.[128] A few sources are available to consider this. National Oceanic and Atmospheric Administration (NOAA) has developed Social Vulnerability Index (SoVI), a tool that measures a region's vulnerability to natural hazards by analyzing the 2010 Census-block or census-tract-level data on incomes and poverty rates to identify the vulnerabilities of poor and disadvantaged communities to climate disruptions. The "Social Vulnerability Index" may be an indicator of a community's need to plan for low-income populations and lack of access to jobs as a threat multiplier for disruptive climate events. To this extent, indirect costs of SLR and flooding are harder to quantify because they are not based on direct measures of damaged property. Figure 20 and Figure 21 illustrate the overall SoVI index and the theme-specific data for Norfolk.

Another metric for identifying the risks posed by poverty and income inequality[129] is a region's Gini Coefficient.[130] The coefficient, as an index of income inequality, serves as a measure of how significant rates of income inequality can prove to be a major risk multiplier for sensitivities to climate risks. The Gini Coefficient is calculated with a value between 0 and 1, with 0 indicating absolute equality of income, and 1

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[126] Per communications and comments from Henry R. ("Speaker") Pollard, V.
[127] Per communications and comments from Henry R. ("Speaker") Pollard, V.
[128] FHWA (2016b).
[129] Income inequality refers to the range to which income is distributed unevenly across the population.
[130] ODU (2015).

indicating total inequality; equivalent of a single person capturing all income benefits. Norfolk's Gini coefficient is 0.473, higher than the Virginia Commonwealth rate of 0.461, and the US rate of 0.469.[131] Norfolk's demographic profile suggests similar indications of the city's below-average economic status.

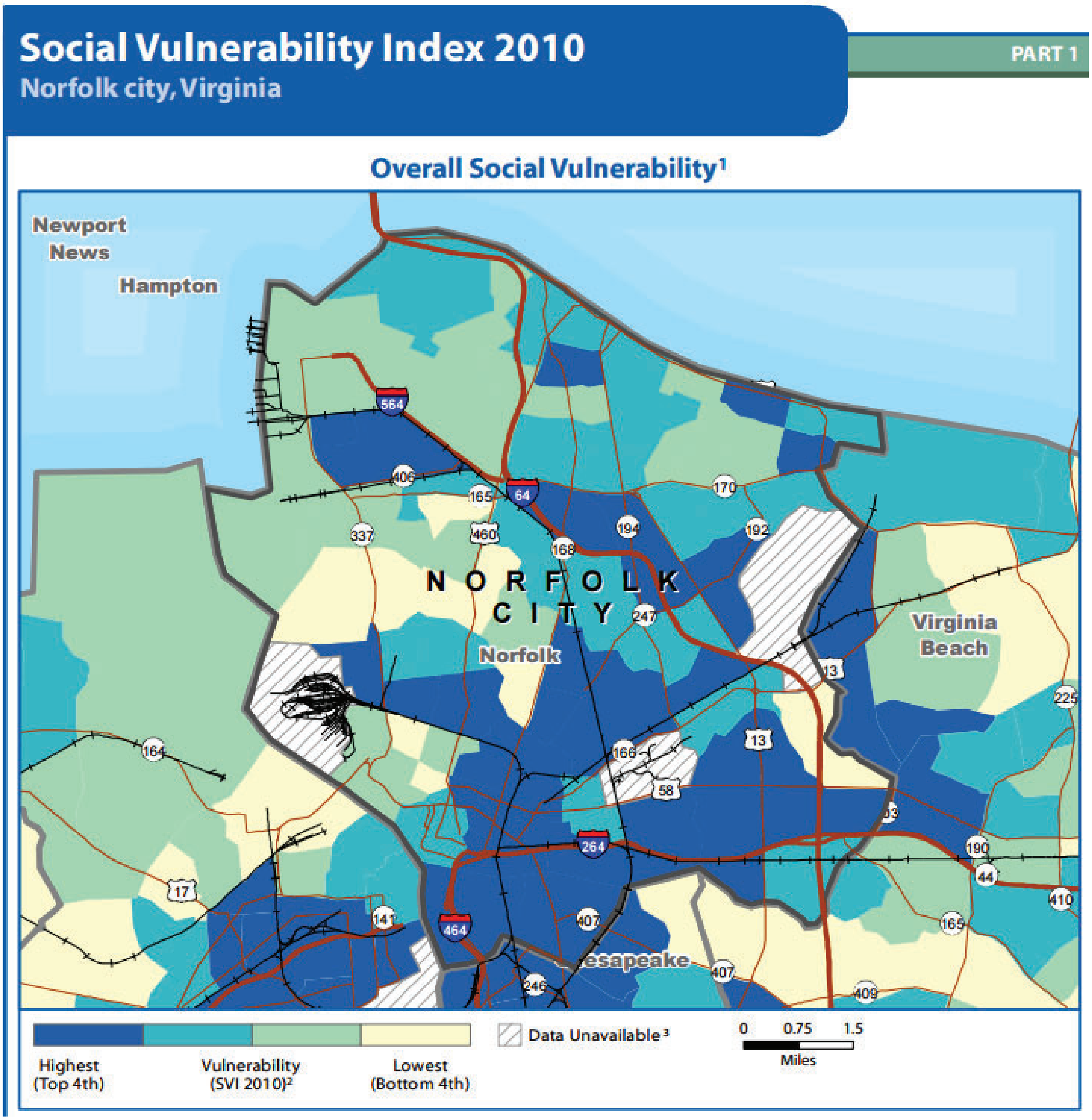

Figure 20. Social Vulnerability Index for Norfolk, Virginia; highest vulnerability is shaded in blue and lowest vulnerability is shaded in yellow (Source: http://svi.cdc.gov/PreparedCountyMaps.html)

[131] As a point of comparison, Philadelphia had a ratio of 0.5020; New Orleans a ratio of 0.5521; and Manhattan a ratio of 0.5994.

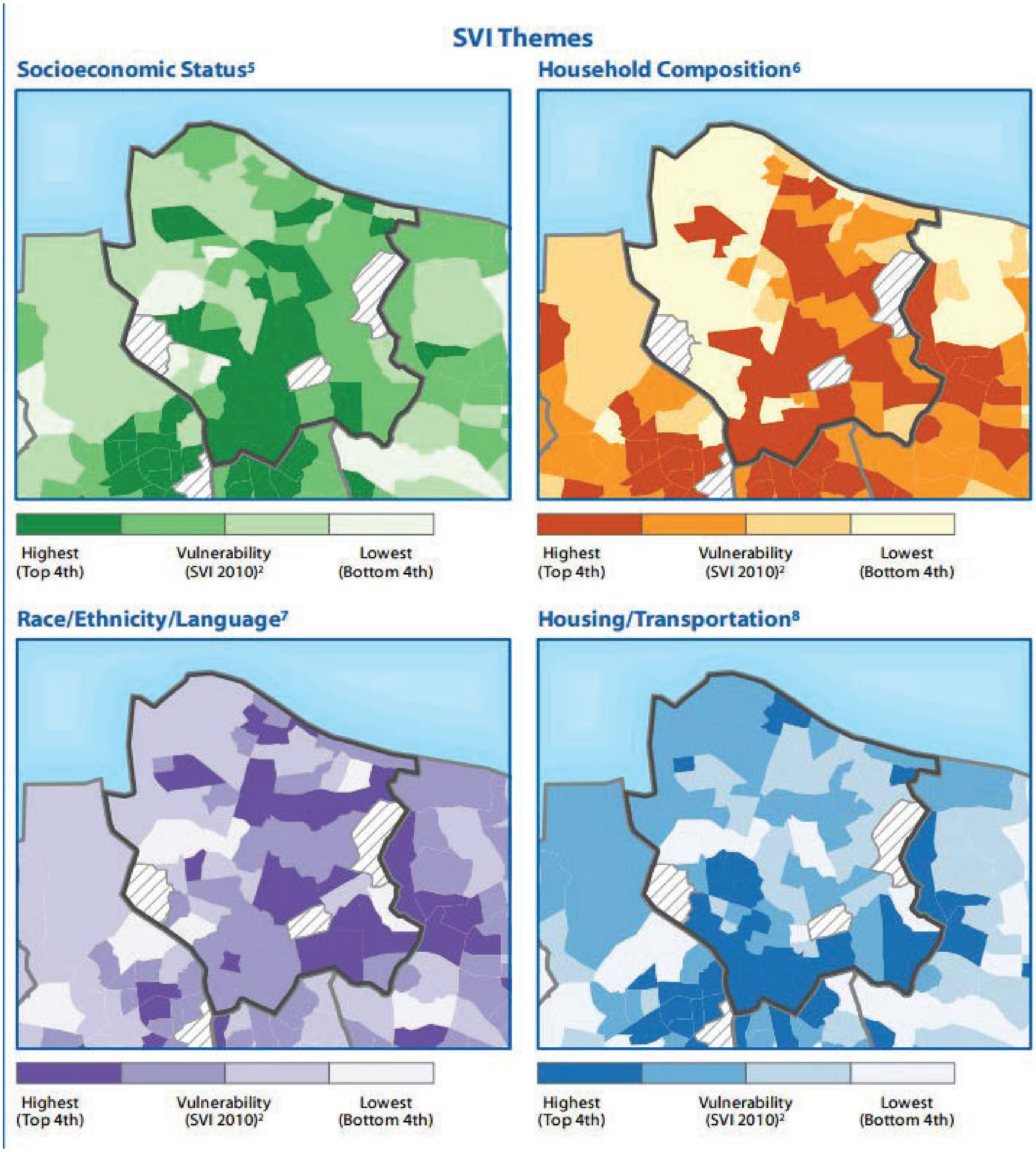

Figure 21. Theme-specific data on social vulnerability in Norfolk from the Social Vulnerability Index; darker colors reflect higher vulnerability (Source: http://svi.cdc.gov/PreparedCountyMaps.html)

1-3 – DATA DESCRIBING ASSET EXPOSURE TO CLIMATE STRESSORS

To describe HR region's asset condition, we need to identify the climate stressors and quantify the scale of the damages and disruption in key transportation functions. Note that the purpose of this section is not to present a formal assessment of all climate-related infrastructure risks in HR or Norfolk. Instead, the purpose is to present high level findings of the available studies and data.

Climate stressors are defined as climate or weather events that pose a threat to the transportation system.[132] The following climate stressors have been identified as concerns for HR: (1) sea level rise (SLR), (2) storm surge due to hurricanes and nor'easters, (3) extreme heat days, and (4) heavy precipitation events.

For assessing how various manifestations of climate change impact the transportation infrastructure, there a number of possible climate stressors that can be considered. Table 35 provides examples of impacts of climate stressors on transportation assets. Of these climate stressors, SLR and storm surge are the greatest concern amongst HR stakeholders.

Table 35. Example of climate stressors and damage mechanism on transportation infrastructure (Source: USDOT (2012b))

STRESSOR	ASSET TYPE	DAMAGE MECHANISM
INCREASED PRECIPITATION	• Culvert and storm drain network	• Flooding
SEA LEVEL RISE	• Navigable waterway bridge	• Clearance for navigation
	• Bridge approach embankment	• Slope erosion
	• Coastal roadways, highways, rails, tunnels	• Flooding
	• Pipelines	• Saltwater intrusion causing corrosion
HIGHER STORM SURGE	• Bridge abutment	• Abutment scour
	• Bridge segment	• Wave forces/bridge pier scour • Overtopping/slope erosion
	• Coastal roadways and highways	• Overtopping/slope erosion
TEMPERATURE CHANGE	• Rail	• Equipment failure • Buckling of rail
	• Roadway and highways	• Rutting and shoving of pavement

[132] National Cooperative Highway Research Program (n.d.).

1-3-2 Coastal Flooding

Recurrent flooding

Recurrent flooding is generally associated with high tides that occurs with some frequency over land, also termed "nuisance flooding."[133] This form of flooding can be considered low-magnitude/high probability events. There are coastal areas throughout HR that are susceptible to frequent minor-to-moderate shallow coastal flooding events (see Figure 22). For example, Norfolk currently experiences nuisance flooding on a monthly basis.[134]

Nuisance flooding, according to NOAA, "has increased on all three U.S. coasts, between 300 and 925 percent since the 1960s."[135] These events are likely to have significant cumulative impact on the built environment and social/ecological systems over the coming decades.

Recurrent Flooding Example: Sandbridge Resort Community

The Sandbridge resort community consists of 5 miles of secluded beach located adjacent to Back Bay National Wildlife Refuge (BBNWR), an 8,000-acre freshwater refuge with large sand dunes, maritime forests, and freshwater marshes. Sandbridge is a very important community to the City of Virginia Beach as it is a popular vacation destination for tourists and residents. It consists of approximately 280 households and has 44 businesses with 238 employees. However, Sandbridge is not easily accessible with only one public roadway approximately 5.3 miles long connecting the community, Sandbridge Road. Sandbridge Road has a range of 5,500 to 17,000 vpd (vehicles per day) and is an evacuation route. However, Sandbridge Road, among other roadway safety concerns, experiences nuisance flooding. The 100-year FEMA base elevation for that area is 4.0 feet above the North American Vertical Datum of 1988 (NAVD 88). Sandbridge Road elevation ranges from 1.0 ft to 3.5 ft, which does not even meet current standards. Without a modification, the existing low-lying elevation of the roadway would continue to be problematic causing re-occurring flooding which will only worsen with sea level rise.

Source: Adapted from communication with Phil Pullen, P.E.

[133] NOAA (2014a).
[134] NOAA (2014b).
[135] NOAA (2016).

Figure 22. Areas currently susceptible to shallow coastal flooding in Hampton Roads, inset Norfolk (Source: NOAA Sea Level Rise Viewer)

Figure 23 identifies the number of flood events for road segments over about a 4 year period. It is not known from Figure 23 what caused the flooding (e.g., extreme event or high tide), but those road segments that experience a higher level of flooding may be in areas prone to recurrent flooding. The roadways that experience more frequent flooding align somewhat with the areas currently susceptible to shallow coastal flooding (though this is a bit difficult to distinguish).

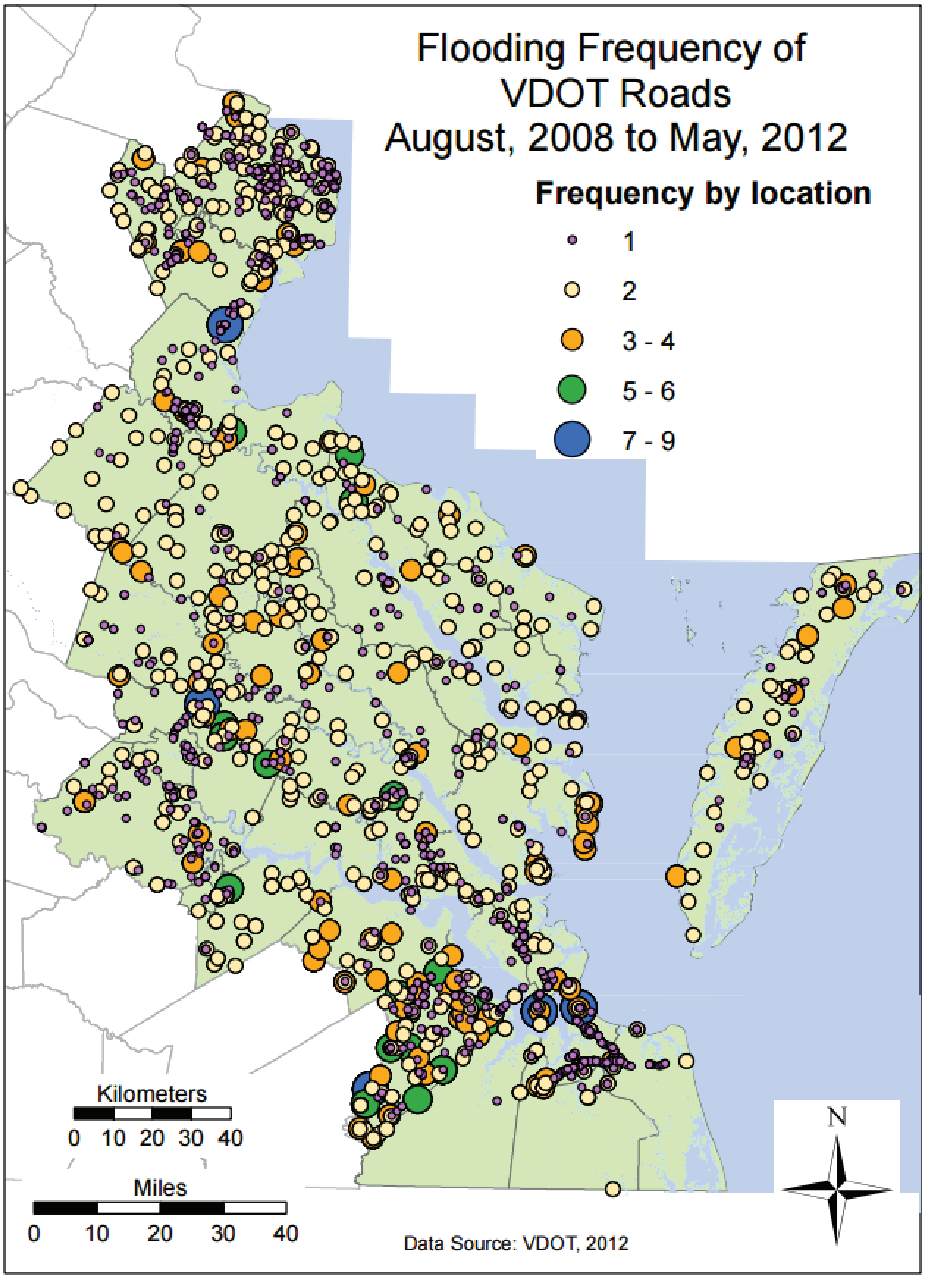

Figure 23. Flooding frequency of VDOT Roads (frequency summed over 2008-2012) (Source: VIMS (2013))

Sea Level Rise

In HR, the majority of the region's 2,900 square miles of development is located in low-lying land, no more than a few feet above sea level.[136] This places a number of transportation assets at risk to coastal flooding.

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136 HRTPO (2013b).

This section considers the historical and projected rate of sea level rise (SLR) for HR; illustrating the potential increase in flood threat to a number of transportation assets.

Global SLR. Globally, sea level has risen at a rate of 1.7±0.2mm (0.07 inches) per year from 1901 to 2010, accelerating to a rate of 3.2±0.4mm (0.13 inches) per year from 1993 to 2010 (see Figure 24).[137] Since 1992, sea level observations have improved through the use of satellite data.[138]

As shown in the figure below, NOAA suggests a risk-based scenario range of 0.2 meter (0.7 feet) to 2 meter (6.6 feet) relative to the year 1992.[139] Future rates are informed by a wide variety of analysis from semi-empirical methods to global climate modeling using various assumptions about future conditions. This results in a range of plausible future SLR by end of century, this range illustrates much of the uncertainty in the state of the science (e.g., rate of melting of glaciers and ice sheets) and regarding how global society may evolve (e.g., fossil-fuel use, population growth, etc.).

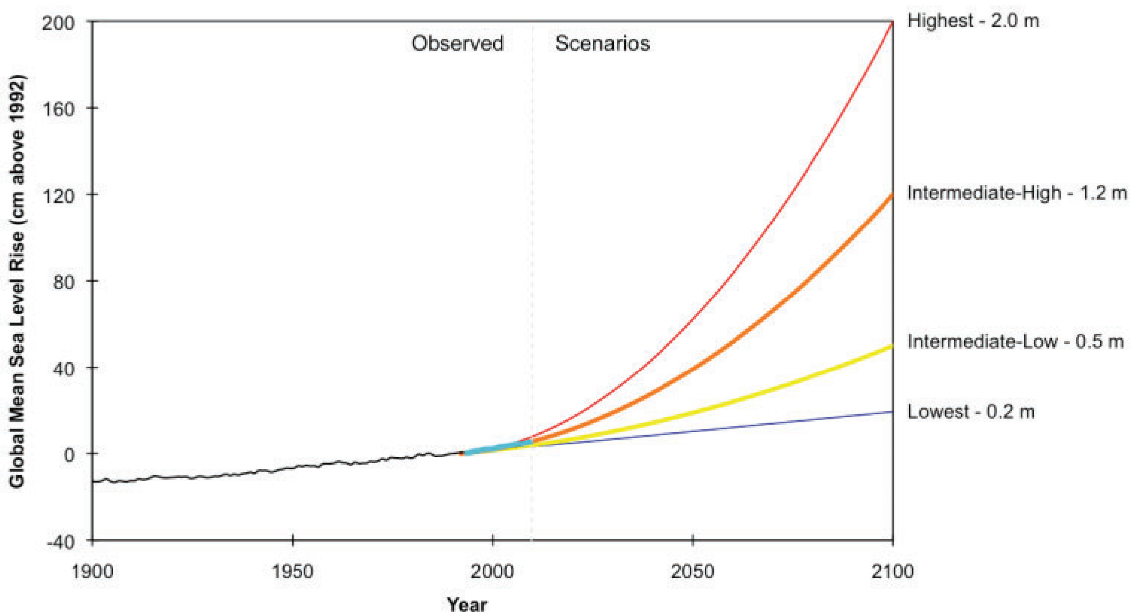

Figure 24. SLR projections, 1800 – 2100 (Source: NOAA (2012))

[137] Church, John A. et al. (2013).
[138] U.S. Global Change Research Program (2014).
[139] USGCRP (2014).

Local Sea Level Rise (SLR). The HR region has experienced local SLR (also termed relative SLR) greater than the global average. Local or relative SLR accounts for both global SLR such as caused by thermal expansion and melting of glacier and ice sheets and changes in local factors such as land subsidence, tidal patterns, and ocean density. For HR, the rate of local rise has been driven, in part, by land subsidence primarily in response to the disappearance of huge ice sheets which had caused a bulging in the Earth's crust around Virginia.[140, 141] In addition, the observed sinking along the coastline may also be exacerbated by groundwater withdrawal.[142] Another factor impacting SLR, in the HR region and beyond, is the measured slowing of the Gulf Stream current in response to changes in ocean currents.[143]

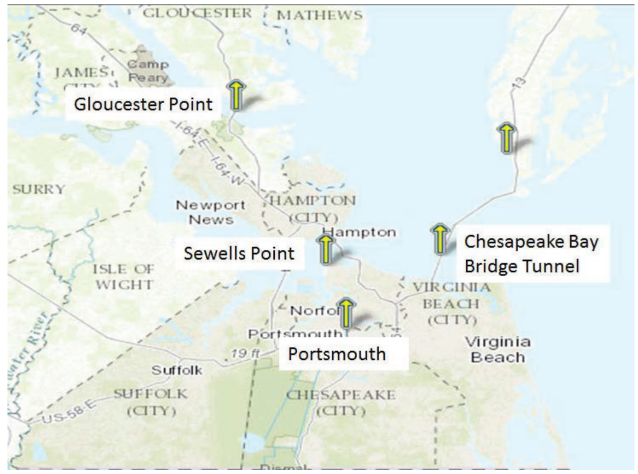

Figure 25. Sea level trends at NOAA tide gages within HR area (yellow area indicates a rise of 1 to 2 feet over the past century) (Source: NOAA Tides and Currents)

The HR region has a number of tide gages, all of which have measured an estimated increase of about 1 to 2 feet over the past century (see Figure 25), which is greater than the estimated historic global SLR of 0.6 feet (see Table 36). Though measured local SLR varies by tide gage in HR, the collective evidence suggests sea level is rising and at a greater rate than the global average. Given recurrent flooding is already an issue in HR, these findings would provide further support for considering ways to adapt to rising coastal waters.

Table 36. Mean sea level trends and estimated total rise for each of the HR NOAA tide gages (Source of data: NOAA Tides and Currents)

LOCATION	DATA RECORD	MEAN SEA LEVEL TREND (MM/YEAR) USING DATA RECORD	TOTAL RISE (CHANGE IN FEET OVER 100 YEARS)
GLOBAL	1901-2010	1.7 +/- 0.2 mm/year	0.6
SEWELLS POINT	1927-2015	4.59 +/- 0.23 mm/year	1.51
PORTSMOUTH	1935-1987	3.76 +/- 0.45 mm/year	1.23
CHESAPEAKE BAY BRIDGE TUNNEL*	1975-2015	5.93 +/- 0.77 mm/year	1.95
GLOUCESTER POINT	1950-2003	3.81 +/- 0.47 mm/year	1.25

**The mean sea level trend is higher than the other HR tide gages, likely in part because the trend is based on recent data during a time global sea level rise has accelerated.*

Considering the global SLR scenarios, a recent HRTPO/HRPDC (2016) report developed local sea level rise projections for Sewells Point relative to the year 1992 (see Figure 26). The choice of both local SLR scenario

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[140] Virginia Institute of Marine Science (VIMS) (2013).
[141] Geologically, land subsidence is primarily driven by plate tectonics of post-glacial isostatic adjustment.
[142] Virginia Institute of Marine Science (VIMS) (2013).
[143] Although this topic is beyond the scope of this paper, reports on the Gulf Stream's slowing issue have been discussed in a variety of publications. See for example: https://www.odu.edu/news/2013/2/gulf_stream_sea_leve#.V6yVbU1TFLM.

and the future planning time horizon will directly affect which transportation assets are identified as exposed to future flooding. This is a critical decision point when considering an economic quantification analysis.

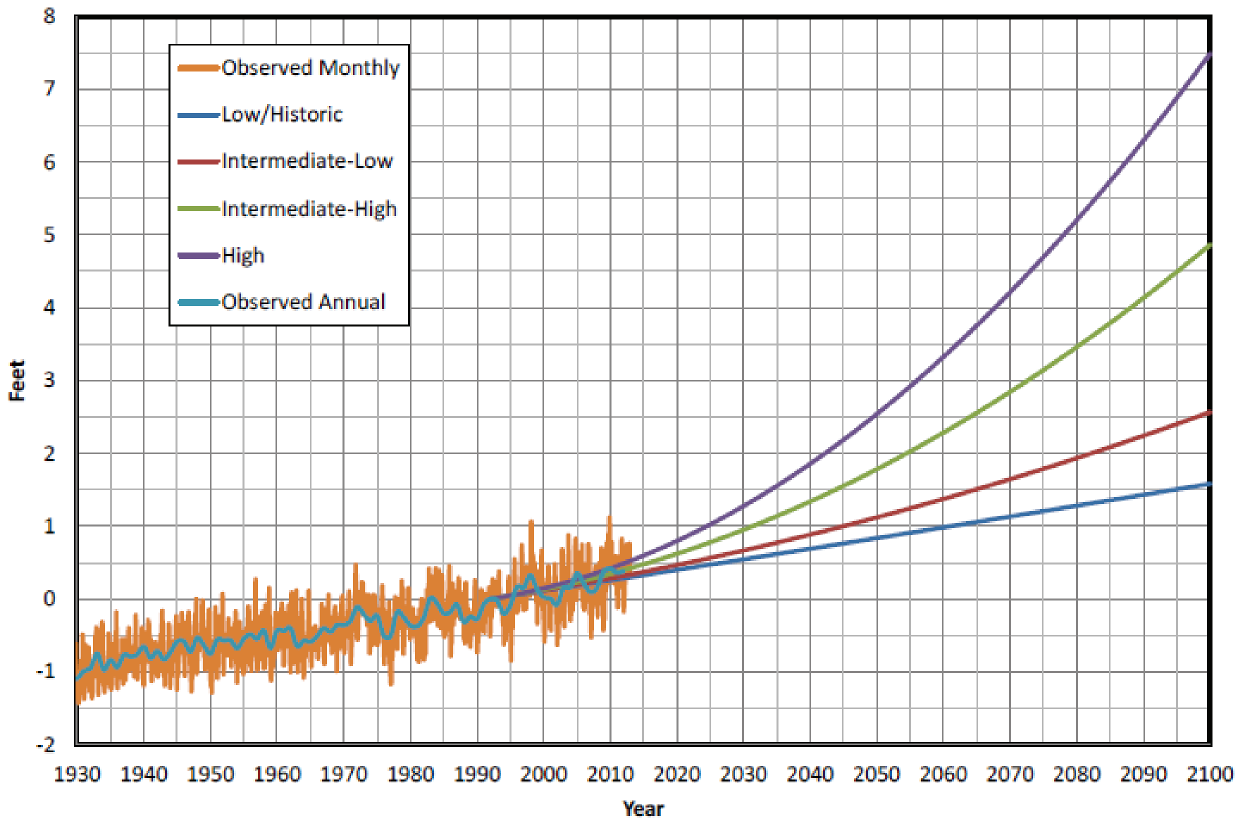

Figure 26. Observed and projected changes in sea level for Sewells Point tide gage (Source: HRTPO/HRPDC (2016))

NOAA's Sea Level Rise Viewer is a publically available web mapping tool that illustrates coastal flooding if sea level rise were to rise from 0 to 6 feet (at 1 foot increments) above average high tides (mean higher high water). Figure 27 shows coastal flooding in light blue shading within the Hampton Roads region under two feet of SLR. The bright green shading shows low-lying areas that will only flood if there is a means for water to flow into these areas (i.e., additional analysis is necessary to determine if these areas will, in fact, flood).

Figure 27. Coastal flooding at high tide for Hampton Roads with 2 feet SLR, inset Norfolk (Source: NOAA Sea Level Rise Viewer)

A number of low-lying jurisdictions within HR are considered vulnerable to SLR. Poquoson's elevation is below 10 feet along with much of Hampton and Norfolk.[144] Though Virginia Beach and Chesapeake are low-lying areas, much of the developed sections are at higher elevations. SLR not only contributes to coastal flooding but can cause erosion along coastal areas.

NOAA Sea Level Rise Viewer also considers future changes in shallow coastal flooding (see Figure 28). For the Sewells Point tide gage, NOAA Sea Level Rise Viewer suggests there are about 11 flood events per year (based

[144] VIMS (2013).

on 2007-2009 data) with flood duration totaling 2 days per year. Under a SLR of 0.5 meter (1.6 feet), NOAA estimates an increase to 345 flood events per year with flood duration totaling 53 days per year. This suggests there could be a flood event during the highest high tide almost every day of the year. For SLR of 1 meter (3.3 feet), the number of flood events per year could increase to 616 suggesting a flood event occurring almost every high tide (i.e., two high tides a day), with cumulative flood conditions lasting a total of 233 days per year. At this frequency, the land type would likely evolve into a wetland condition of saturated soils.

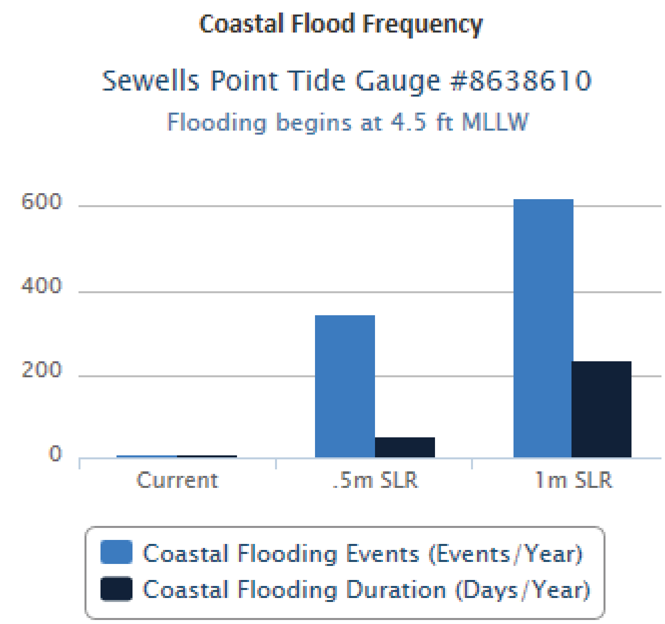

Figure 28. Flood frequency at Sewells point (Source: NOAA Sea Level Rise Viewer)

Storm surge

Coastal flooding is directly proportional to the storm surge, defined as the height of water above the predicted astronomical tide.[145] HR is vulnerable to storm surge from both tropical storms (e.g., hurricanes) and nor'easters. For the southeastern United States, recent research suggests that tropical storms represented 44 of the top 50 storm surge events between 1923 and 2008.[146] Within HR, the southeastern coastal area has experienced a greater number of coastal county hurricane strikes compared to the rest of HR (see Figure 29). These storms produce significant winds leading to damaging coastal flooding. The impacts of storm surge can be significant, and experts have emphasized that the destructive force of this phenomenon on built infrastructure has been underestimated,[147] as many focus solely on sea level rise. For example, the three primary impacts to the region's road network include: flooding of evacuation routes, increased hydraulic pressure on tunnels, and alteration to drainage capacity.[148] The severity of coastal flooding will worsen with

[145] NOAA (n.d.(a)).
[146] Grinstead et al. (2012).
[147] Botts et al. (2014).
[148] HRTPO (2013b).

sea level rise, prompting increased interests for developing adaptive measure to reduce the impacts of future flood events.[149]

One model routinely used by NOAA National Hurricane Center (NHC) and the climate community to simulate storm surge is NOAA National Weather Service's (NWS) Sea, Lake and Overland Surges for Hurricanes, or SLOSH model. SLOSH is a two-dimensional numerical model that estimates storm surge associated with historical, predicted, or hypothetical hurricanes by using storm parameters[150] to model the wind fields.[151] The SLOSH display program plays a useful role in helping emergency managers prepare for forecasted storms by illustrating forecasted storm surge.[152] Some climate vulnerability and/or screening assessments concerned with coastal inundation from storm surge have used SLOSH as an indicator of potential inundation exposure.[153] A drawback of using SLOSH is that the model does not consider: the impacts of waves on top of storm surge; tides on top of storm surge; normal river flow and rain flooding.[154]

Figure 29. Hurricane strike frequency by county (Source: NOAA Historical Hurricane Track)

Recent analysis in HR has, instead, used ADCIRC modeling. ADCIRC can be simulated using either two or three dimensions and uses finite element analysis, allowing freedom in defining the latitude/longitude and elevation grid. This is particularly useful for storm surge analysis in that the storm can be modeled at a very fine resolution (e.g., 100 meters compared to 1km for SLOSH).[155] A drawback of ADCIRC is that it is computationally intensive, requires expensive elevation datasets using the remote sensing method Light Detection and Ranging (LiDAR),[156] and the results may not add significant value compared to SLOSH results, depending on the location and use.[157]

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[149] VIMS (2013).
[150] Storm parameters include atmosphere pressure, forward speed, and track. NOAA (n.d. (b)).
[151] The NHC study notes that the SLOSH model serves as the basis for a number of storm-surge models, and that regional emergency response (ER) managers have been using the model's data displayed in the SLOSH Display Program (SDP) to visualize forecasted storm surge. However the tool does not explicitly model the impacts of waves or tide on top of storm surge, nor does it account for normal river flow and rain flooding. See: http://www.nhc.noaa.gov/surge/slosh.php.
[152] VIMS (2013).
[153] Tate and Frazier (2013).
[154] VIMS (2013).
[155] Lin et. al. (2012).
[156] NOAA (2015).
[157] Lin et al. (2010).

Recent SLR/storm surge transportation vulnerability studies

Two recent assessments considered the impact of coastal flooding on HR:

- HRTPO (2016) analysis of HR roadway exposed to inundation under three scenarios to help inform the 2045 long-term transportation planning effort.
- Virginia Institute of Marine Science (VIMS) (2013) analysis that identified and illustrated coastal inundation overlaid with a number of layers of socioeconomic, natural environment, and built environment for SLR scenarios to help inform the 2043 long-term transportation planning effort.

These studies model HR's future exposure to coastal inundation. The VIMS (2013) analysis moves beyond just identifying exposure, with additional information provided below for completeness. Each is discussed below.

Quantifying Impacts of SLR

In Norfolk, there are three key relationships of vulnerability to flooding risks that make it difficult to fully quantify the impacts of SLR: a) indirect costs of recurrent flooding and uncompensated losses from business interruption; b) high poverty rates and wealth disparities that exacerbate the impacts; and c) lack of adequate private insurance protection that blurs the lines between public and private assets.

HRPTO (2016) study. With the growing recognition of the risks of SLR threatening Virginia coastal areas, HRTPO recently completed a study illustrating the areas and roadways within HR that may be submerged under 2 feet of relative SLR relative to the year 1992 (see Figure 30).[158] This study considered 2 feet as a possible level of SLR useful for informing the region's 2045 long-term transportation planning. In addition to SLR, the analysis considered storm surge inundation using the Region III Federal Emergency Management Agency (FEMA) ADCIRC modeling results for a 25-year storm surge and 50-year storm surge occurring "on top of" the relative SLR (i.e., the storm surge layers were "added" to the 2 foot SLR layer, with some additional processing to treat low elevation areas that are not tidally connected).[159]

[158] HRTPO (2016).

[159] The 25-year storm surge which has a 4 percent chance of occurring within any given year (based on historic records) is associated with water rise of 8.1 feet North American Vertical Datum (NAVD 1988) for Sewells Point. The 50-year storm surge which has a 2 percent chance of occurring within any given year is water rise above the surface of 8.8 feet NAVD.

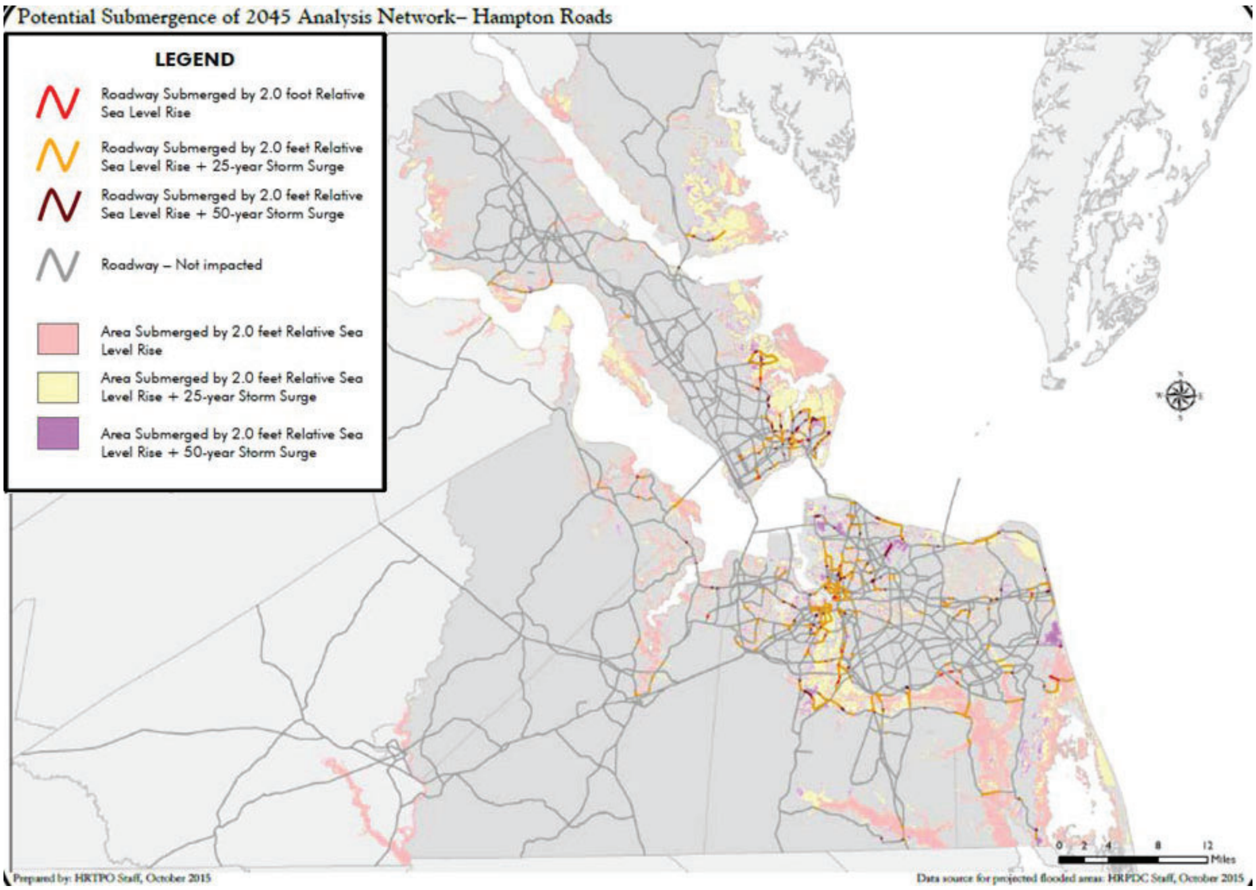

Figure 30. Hampton Roads with 2 feet SLR (Source: HRTPO (2016))

The HRTPO report suggests that existing roadways in Virginia Beach, Hampton, Norfolk, Newport News, and the Chesapeake could experience impacts if relative sea level were to rise 2 feet (relative to 1992 sea level). This is expanded to a number of additional jurisdictions when also considering the 2045 Analysis Network, with the greatest potential flooding of roadways occurring in Gloucester County and Poquoson (see Table 37). Considering storm surge with a 2-foot relative SLR introduces significant concern for many of the jurisdictions in HR, specifically Poquoson, Portsmouth, Norfolk, and Hampton where more than 10 percent of the roadways could be flooded under a 25-year storm surge. This increases quite a bit when the 2045 Analysis Network is included in the analysis – e.g., with a majority of roadways in Poquson being submerged under the 25-year storm surge and almost all roadways being submerged under the 50-year storm surge.

Table 37. Potential submergence of 2045 analysis network and existing roadways by Jurisdiction (HRTPO (2016))

Hampton Roads Jurisdiction	Total Centerline Miles	Scenario 1: 2 Ft Sea Level Rise		Scenario 2: 2 Ft Sea Level Rise + 25-Yr Storm Surge*		Scenario 3: 2 Ft Sea Level Rise + 50-Yr Storm Surge*	
		Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded
Chesapeake	1,213	3.1	0.3%	143.4	11.8%	177.3	14.6%
Gloucester County	653	15.7	2.4%	96.9	14.8%	106.1	16.2%
Hampton	698	3.6	0.5%	197.7	28.3%	247.5	35.5%
Isle of Wight County	680	0.4	0.1%	4.0	0.6%	4.5	0.7%
James City County	592	0.3	0.1%	8.6	1.5%	9.4	1.6%
Newport News	746	0.5	0.1%	15.8	2.1%	20.1	2.7%
Norfolk	948	5.2	0.5%	205.9	21.7%	272.9	28.8%
Poquoson	57	1.8	3.1%	48.4	84.5%	55.2	96.5%
Portsmouth	487	0.2	0.0%	114.3	23.5%	151.1	31.0%
Suffolk	854	0.2	0.0%	3.3	0.4%	4.3	0.5%
Virginia Beach	1,858	5.1	0.3%	129.6	7.0%	160.7	8.6%
Williamsburg	75	-	0.0%	0.1	0.1%	0.1	0.1%
York County	654	1.3	0.2%	45.0	6.9%	57.7	8.8%
	9,516	**37.5**	**0.4%**	**1,013.0**	**10.6%**	**1,267.0**	**13.3%**

** Centerline miles are cumulative for Scenarios 2 and 3. For example, Scenario 2 includes roadway segments from Scenarios 1 and 2. Scenario 3 includes roadway segments from Scenarios 1, 2, and 3.*

The HRTPO analysis is particularly helpful in understanding exposure to coastal inundation. This analysis can inform an economic quantification analysis by: (1) by drawing on the identification of which roadways may be submerged under these various future scenarios; and (2) using the series of GIS SLR and storm surge inundation layers to identify additional exposed transportation and sector-specific infrastructure.

VIMS (2013) study. An earlier study was conducted by the Virginia Institute of Marine Science (VIMS) to develop tools for estimating relative SLR risks to reduce some of the gaps when using climate data for long term project planning, including its absence in the HRTPO 2034 Long Range Transportation Plan (LRTP).[160] Using these tools, VIMS identified segments of the Virginia coastal areas (also known as the "Tidewater," this region includes HR) that are exposed to recurrent flooding of the roadways. This section serves as a brief summary of the tools and key discussion points of VIMS' *Recurrent Flooding Study for Tidewater Virginia* (2013) report.

[160] HRTPO (2012a).

For the Tidewater, VIMs estimates future SLR ranging from 1.6 to 7.5 feet between 1992 and 2100 based on four global SLR scenarios used by the recent U.S. National Climate Assessment. For planning purposes and drawing on these four global SLR scenarios, VIMS suggests that 1.5 feet of SLR is a reasonable estimate for the amount of SLR to occur in the Tidewater sometime between 2032 and 2065.

Example: Hurricane Isabel

Hurricane Isabel, initially a Category 5 storm that by the time of landfall in the region was reduced to a Category 1 storm, resulted in a storm surge of 5.13 feet above mean higher high water at the Sewells Point tide gauge, only slightly below the historical maximum flood of 5.26 feet above mean higher high water. Had the storm coincided with either a new moon or a full moon, higher maximum water levels could have occurred.

Source: NOAA (2004).

For simulating future storm coastal inundation between 2032 and 2065, VIMS suggests using a 3 foot storm surge on top of the 1.5 foot SLR to simulate vulnerability to future storm coastal inundation. This storm surge level was chosen as it is similar to that which has been experienced in the past. However, it is noted that storm surge can well exceed 3 feet. For example, Sewells Point tide gage recorded a 4.2 foot surge for Hurricane Irene in 2011 (also see textbox entitled "Example: Hurricane Isabel"). VIMS created a summary table of all coastal locations in coastal Virginia vulnerable to such a rise in water level. Table 39 shows the levels of vulnerability at several HR jurisdictions.[161]

Table 39. Top 7 HR Jurisdictions with vulnerability to a rise in water level of 4.5' (based on mean SLR of 1.5' and storm surge of 3') (Source: HRPTO (2013b))

HR JURISDICTIONS	TOTAL AREA (ACRES)	PROPORTION OF AREA WITH POTENTIAL TO FLOOD*	PROPORTION OF FLOOD-PRONE AREA DEVELOPED**	TOTAL FLOOD-PRONE DEVELOPED AREAS (ACRES)	CENTERLINE ROAD MILES PRONE TO FLOODING
NORFOLK	34,723	12%	60%	2,500	119
PORTSMOUTH	21,578	9%	57%	1,107	51
HAMPTON	33,171	15%	28%	1,393	50
CHESAPEAKE	217,011	11%	11%	2,626	103
VIRGINIA BEACH	145,465	26%	11%	4,160	289
POQUOSON	9,882	69%	11%	750	38
NEWPORT NEWS	44,297	13%	8%	461	15
TOTAL	**506,127**			**12,997**	**665**

**Proportion of location at risk of increasingly frequent flooding over the next 20-50 years;*
***Proportion of potentially flooded area currently classified as developed land;*

The Table above underscores the high level exposure in Norfolk to the risks of SLR and storm surge, compared to most other HR jurisdictions (with the possible exception of Virginia Beach and Chesapeake). The Table shows that while only 12 percent of Norfolk's total acres (4,167 acres) has the potential to flood, 60 percent of those acres in vulnerable area are developed parcels (a total of 2,500 acres and 119 miles of road), potentially

[161] The data, as reported by HRTPO, are based on the benchmarks derived from the VIMS (2013) report.

exposing many structures to flooding from SLR. This contrasts with Poquoson, where 69 percent of its acres have the potential to be flooded, but with only 11 percent of that land developed, only 750 developed acres are likely to be flooded.[162]

Exposure risks for Norfolk's highway infrastructure are also higher than the rest of the HR region. Table 39 below compares the exposure data from the HRPDC Phase III study, quantifying the portions of the region's roadway system at risk of exposure (focusing on mid-level estimate of rise of 1 meter above spring high tide). The table shows that about 7 percent of Norfolk's total road miles, and 9 percent of its interstate highway links are at risk of flooding from a 1-meter SLR, compared to 4.3 percent and 5.6 percent, respectively, for the HR region.

Table 39. Exposure to one meter of SLR above spring high tide in Hampton Roads and Norfolk (Source: HPRDC (2013))

ROAD INFRASTRUCTURE	HR REGION (ROAD MILES)			NORFOLK (ROAD MILES)		
	Total	Mid-Level Estimate	% of roadway system	Total	Mid-Level Estimate	% of roadway system
INTERSTATE	250	14	5.6	55	5	9.0
PRIMARY	1,460	50	3.4	153	9	5.9
SECONDARY	2,216	72	3.2	0	0	-
LOCAL OR PRIVATE	7,841	371	4.7	943	61	6.5
TOTAL ROAD-MILES	**11,767**	**507**	**4.3**	**1,150**	**76**	**6.6**

1-3-4 Extreme Heat Events

In the past, the Commonwealth of Virginia has experienced heat events severe enough to cause pavement buckling, such as in August of 2010.[163] This section summarizes our analysis of how heat events may change in the future using the Department of Transportation's Coupled Model Intercomparison Project 5 (CMIP5) Climate Data Processing Tool under two emission scenarios (moderately-low and a high) and ten statistically downscaled climate models.[164] Projections were developed for two future time slices, 2034-2054 and 2065-2084. The 2034-2054 future horizon was chosen to align with long-term planning documents and the 2065-2084 future horizon helps inform potential climate conditions that may be experienced within the asset lifetime for long-lived structures.

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[162] The Wetlands Watch has observed that based on the 1.45ft/100yrs SLR assumption, if Sandy happened 100 years ago in 1912 it would've had a storm surge of only 2.64 feet above the benchmarked mean higher high water (MHHW) – i.e., the average of the higher of the two daily high tides over a 19-year cycle. Instead, the Sandy storm surge was 4.09ft above the MHHW. By 2050 this will be 5.59 feet. Source: Wetlands Watch (n.d.).

[163] Bogues (2010).

[164] This tool uses statistically downscaled daily temperature and precipitation data averaged over four 1/8 degree (12km) grid cells centered at Norfolk. The results of changes in heat event and heavy precipitation can provide a qualitative discussion of the direction of change for the HR area. The moderately-low emissions scenario was the relational concentration pathway to a global radiative forcing of 4.5 W/m^2 at the end of the century (i.e., RCP4.5) and the high emissions scenario leads to a global radiative forcing of 8.5 W/m^2 (RCP8.5). The statistically downscaled Reclamation data can be found here: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

High temperatures can affect a number of transportation operations such as construction activities, as well as damage assets such as bridge joints and pavement. Future projections suggest that summertime extreme heat may become an increasing concern in the future. By mid-century, there may be between 17 and 21 days per year above 95°F (see Figure 31). Later in the century, that number could increase to as many as 48 days per year. The duration of hot days may also be in slightly longer stretches, increasing the possibility of heat events. By mid-century, hot temperatures may last 5 to 7 consecutive days per year, compared to the baseline of 3 consecutive days per year. Later in the century, hot temperatures may last one to two weeks.

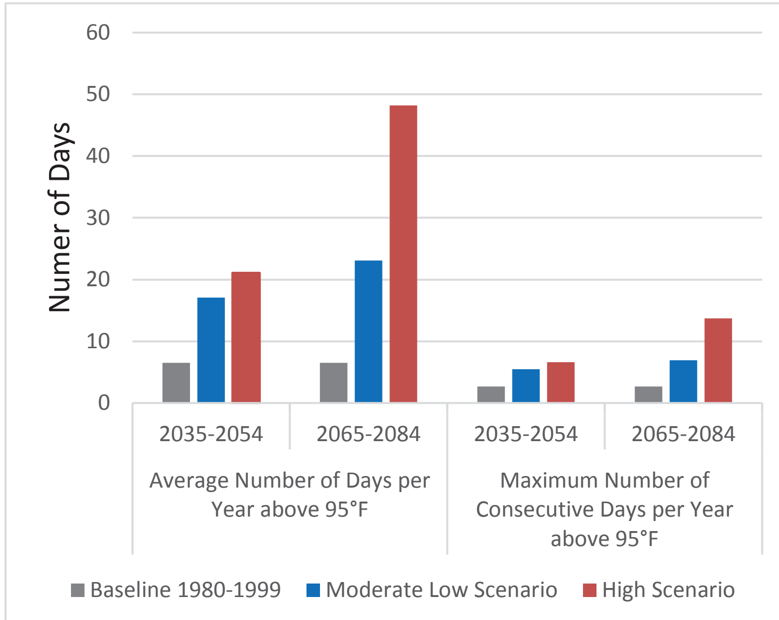


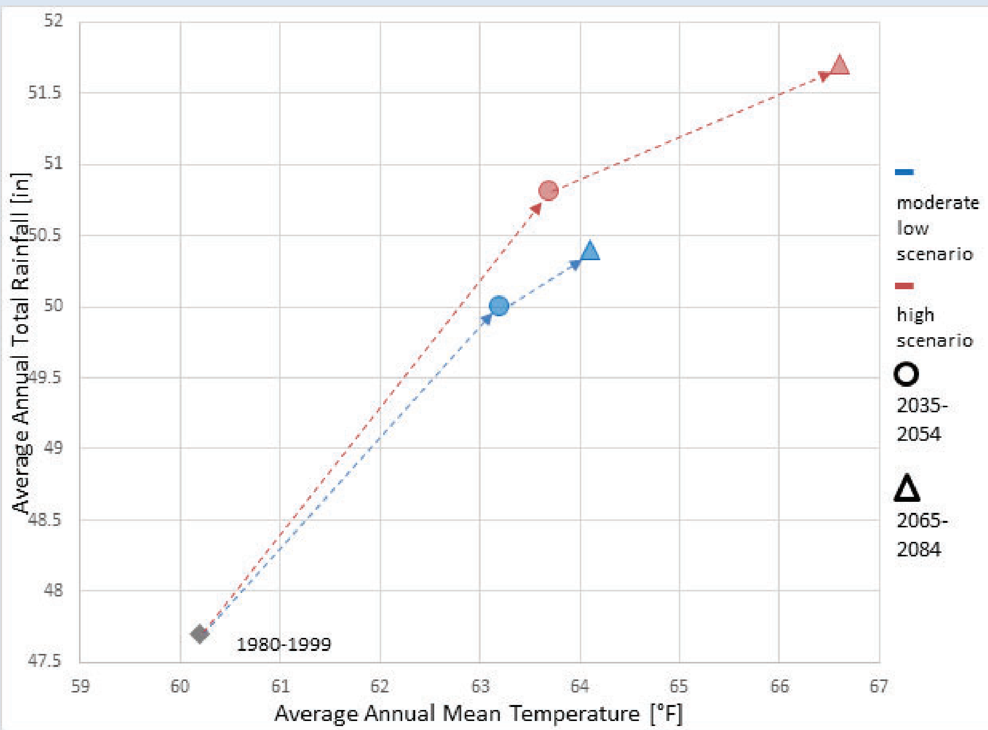
Figure 31. Average number and maximum consecutive number of hot days per year above 95°F

In addition, the highest 4-day average summer high temperature is projected to increase from 95°F to between 98.5°F and 99.3°F by mid-century and to between 99.6°F to 102.9°F in the latter half of the century. Similar increases are projected for the highest 7-day average summer high temperature. These temperature thresholds may be relevant to transportation engineers and planners.

Future Change in Annual Precipitation and Temperature

Under both emissions scenarios (moderately-low and high), Norfolk is expected to be warmer and wetter in the 21st Century. Over the next few decades, annual average temperatures may rise between 3.0°F ±0.5°F and 3.5°F ±0.5°F, with precipitation increasing by 5 percent to 6 percent. In the latter half of this century, temperatures may rise between 3.9°F±0.7°F and 6.4°F ±0.9°F, with precipitation increasing by 6 percent to 8 percent. The largest seasonal increase in precipitation is projected to occur during the winter months (approximately 10 percent increase) regardless of scenario or future time horizon. These changes may not cause dramatic impacts on transportation assets such as a flood event, but these changes may impact transportation planning and the overall integrity of assets through reactionary stressor changes in ecology, vegetation, and soil moisture.

Historic and Projected Changes in Annual Temperature and Precipitation



1-3-5 Heavy Precipitation Events

HR has experienced a number of heavy precipitation events over the past few decades that have led to FEMA disaster declarations and significant flooding. From our analysis using the USDOT CMIP Processing Tool, Figure 32 shows the average number of "very heavy" precipitation events each year.[165] By mid-century, the projections suggest two additional "very heavy" precipitation events compared to the historical record of 11 events per year. Towards the latter half of the century, there may be two to four more events per year. While this is only about a 20 percent increase, it may lead to more flooding, especially when coupled with SLR. In addition, the largest seasonal 3-day precipitation event is projected to increase by about 50 percent during the winter months[166] regardless of the scenario and future time horizon. This is consistent with future projections for North America.

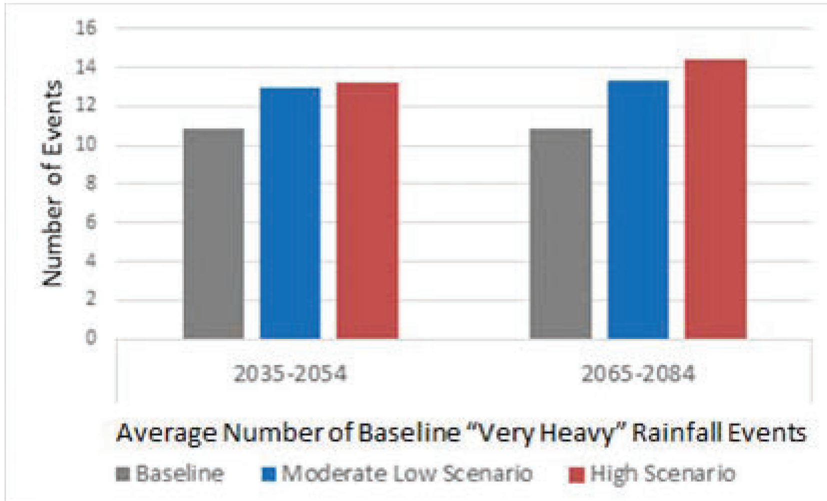


Figure 32. Average number of "very heavy" rainfall events per year

In North America, climate science projections indicate that *likely* outcomes of changing future conditions are increases in precipitation event magnitudes (e.g., depths or intensities), durations, and occurrences (including separate events occurring within very close intervals, i.e., days).[167] As a result, flooding will constitute an increasing concern for transportation assets.

Several current products that identify locations prone to varying levels of flood risk, such as the Federal Emergency Management Agency's (FEMA) Flood Insurance Rate Maps (FIRMs), allow the consideration of impacts to transportation assets and services. To illustrate, FIRMs assist identification of transportation assets affected from floods associated with the 100-year event (aka, base flood or A-zone) or 500-year (X-zones) events and associated floodplains. Given the proper analyses, they may also provide some rough qualification of future projected flood extents and floodplains. For example, as a result of climate change, increased precipitation depths change sufficiently such that the flooding associated with the current 100-year event may only coincide with the future 85-year event. In such a hypothetical example, logically this infers an increase in the precipitation depth associated with the 100-year exceedance frequency. As a result, the future 100-year event would produce an extent of flooding that exceeds the current 100-year FIRM area (but likely not to extend beyond the 500-year floodplain extent). Therefore, at a planning stage, practitioner may be able to then ascertain that those transportation assets

[165] A "very heavy" precipitation event is one that is at or above the 95th percentile of precipitation in the baseline period.
[166] Winter months are defined as December, January, and February.
[167] IPCC (2013).

within the boundaries of the 100-year and 500-year FIRM areas represent those likely associated or affected by future climate conditions.

DOT's quantification study augments the science-based implementation of the Federal Flood Risk Management Standard (FFRMS), based on the authority of Executive Order (EO) 11988, as amended by EO 13690. 80 FR 6424 (2/04/14). The FFRMS, applicable to federally-funded actions (e.g., projects), calls for agencies to use a higher vertical flood elevation and corresponding horizontal floodplain than the base flood for projects to address current and future flood risk, and avoids actions that have negative economic consequences. The FFRMS provides each federal agency some latitude in determining what approach to use to establish the vertical extent of the FFRMS floodplain (i.e., CISA, Freeboard, or 500-year). However, in the case of multiple agency involvement in an action, Step 1 of "Guidelines for Implementing EO 11988 and EO 13690" (Guidelines) (October 8, 2015) encourages early coordination of such agencies to ensure consistent approaches in floodplain determinations. These floodplain determinations necessarily include both the vertical extents and the horizontal extent of the FFRMS floodplain. Therefore, this augmentation study recommends producing a "memorandum of agreement" (or other similar agreement) from Federal agencies that documents agreed upon approaches, processes, and mechanisms for ensuring such consistency of FFRMS floodplain extents and delineations.[168]

1-4 – DATA ON CLIMATE-RELATED IMPACTS ON TRANSPORTATION INFRASTRUCTURE

The HR region has experienced a number of threats that can cause property loss and fatalities. This section identifies past extreme weather events that have been particularly costly for HR and the associated impacts on transportation and the community. In addition, this section presents recent HR studies that have quantified losses due to the impacts of SLR and flooding on transportation.

1-4-1 Impacts to the Transportation System by Past Extreme Weather Events

We used the NOAA's Storm Event Database[169] to identify past storm events that caused enough damage to significantly impact the region (defined in this report as events causing $100,000 or more in property damage). Identifying the impacts associated with past storms can act as a surrogate for understanding sensitivities within the region. This section uses NOAA's Storm Event Database, Spatial Hazard Events and Losses Database for the U.S. (SHELDUS), and FEMA Disaster Declarations Summary to identify recent storms that caused significant economic damages to the region. For these storms, media reports were mined to describe impacts on the transportation system, utilities, environment, and property. This provides insight regarding existing sensitivities to specific types of events.

[168] A discussion of design matters and determinations regarding encroachments to flood plains under 23 CFR parts 625 and 650 is beyond the scope of this study.
[169] NOAA (n.d. (c)),

NOAA's Storm Event Database includes extreme weather events that meet one or more of the following criteria:

- Causes mortality, injuries, notable property damage and/or disruption to commerce (i.e., may be significant event affecting the reliability and integrity of the transportation network);
- Unusual event for a given location that generates media attention (i.e., assets may not be designed/built with these unusual exposures in mind);
- Combination of a significant meteorological event with another event (i.e., assets may be exposed to synergistic impacts).

From 1997 to 2015, the database includes property damages associated with hurricanes, tropical storms, coastal flooding, thunderstorms (lightning and winds), hail, high winds, strong winds, and tornadoes. Prior to 1997 the database is limited to thunderstorms (high wind), tornadoes, and hail. It should be noted that the storm type identifier for a particular storm may not be attributed to the actual weather event type but instead may identify the event's component causing the damage (e.g., heavy wind may in fact be from a nor'easter or tropical storm; a coastal flood may be associated with a tropical storm).

EVENT TYPE	ROUGH ESTIMATE OF PROPERTY DAMAGE (1997 TO 2015)
HURRICANES/TROPICAL STORMS	$585,554,000
FLOODING	$139,111,800
HAIL EVENTS	$17,123,000
HIGH/STRONG WINDS	$5,265,000
TORNADOES	$49,687,000
THUNDERSTORMS	$4,674,000
WINTER/ICE STORMS	$20,120,000
TOTAL	**$821,534,800**

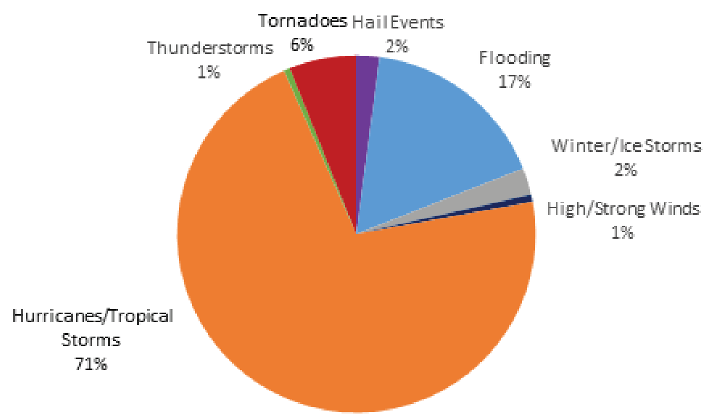


Figure 33. Rough estimate of property damage by storm event type for HR from 1997 to 2012 (nominal values are used so this is a rough estimate) (Source: based on data from NOAA Storm Events Database)

As shown in Figure 33 and 34, hurricane and tropical storms are responsible for the greatest property damage to HR over the past 19 years, followed by coastal flooding. These property damage estimates are rather rough estimates as the NOAA Storm Event Database monetizes property damage of an event by summing across all counties that report this event per the criteria listed above (hence, it's an overestimate as it's not disaggregated to property damages specific to a specific county) and the Database does not adjust property damage amounts to the current year (i.e., doesn't take into account inflation, etc.). If more accurate estimates are needed, a fee-for-service database, The Spatial Hazard Events and Losses Database for the U.S.,

or SHELDUS, is available that uses the data in the NOAA Storm Event Database to provide county-level disaggregated costs (by dividing the event costs equally across counties, which may underestimate or overestimate the actual costs to that county) and accounts for inflation. In addition, SHELDUS is helpful for trend analysis as it includes additional sources of information to provide property damages associated with extreme weather events from 1960 to 2014.

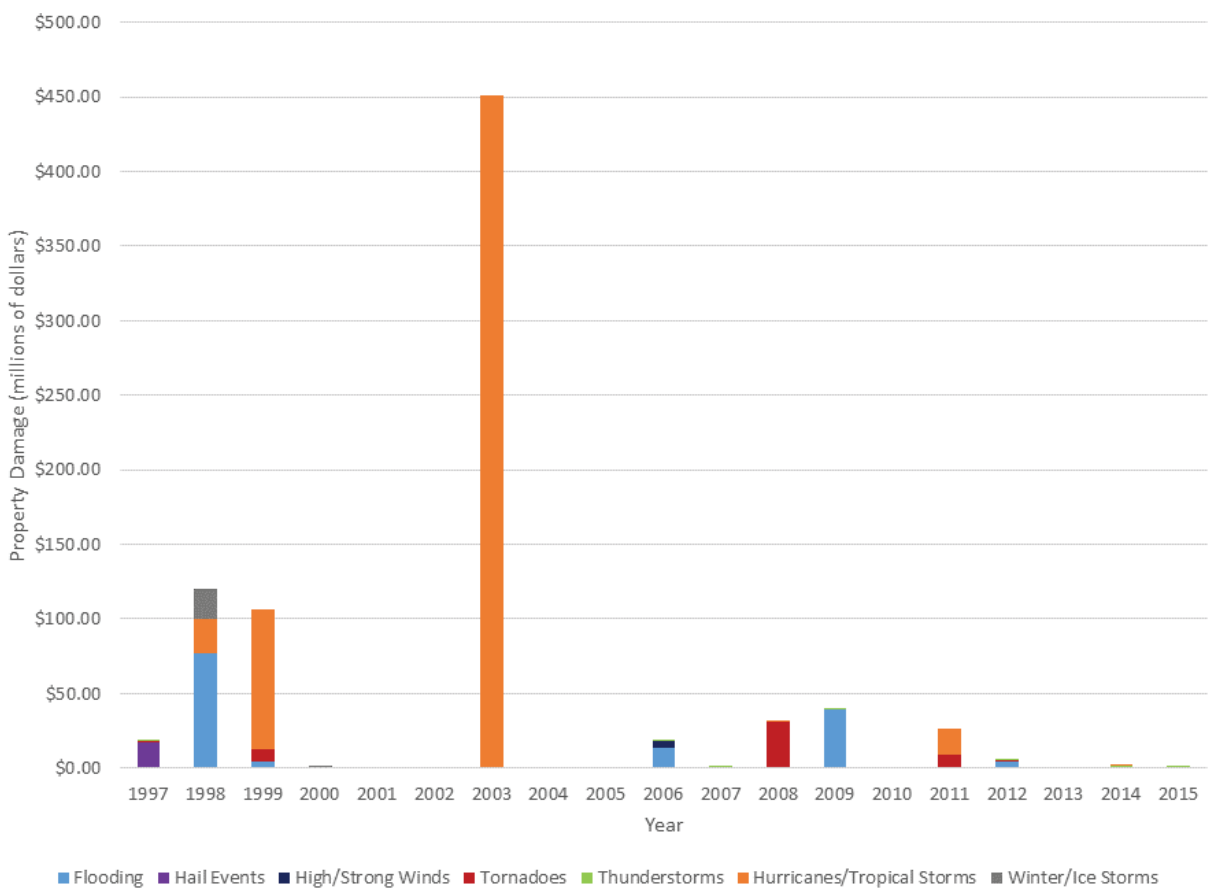


Figure 34. NOAA data on estimated property damage from by storm event type in HR (Source: based on data from NOAA Storm Events Database)

A few additional points were gleaned through inspection of SHELDUS property damage data incurred in Norfolk over that 54-year period: (1) most severe property damage was associated with a handful of relatively infrequent events of large magnitude (30 of the 229 storm events reported more than $100,000 in property damage; 12 of the 229 storm events reported more than $1,000,000 in property damage); and (2) flooding caused by heavy precipitation was as or more costly than flooding caused by a hurricane or coastal surge.

From this analysis, a number of storm events were identified that affected both HR and Norfolk (see Table 40).

Table 40. Storm events that have affected Norfolk and caused at least property damage of at least $100,000 (Source: data from NOAA Storm Events Database)

EVENT	DATE	DAMAGES*
HURRICANE SANDY	10/28/2012	$500,000
HURRICANE IRENE	8/27/2011	$4,500,000
NOR'EASTER	11/12/2009	$18,000,000
SUPERCELLS	4/28/2008	$100,000
NOR'EASTER	11/22/2006	$100,000
TROPICAL DEPRESSION ERNESTO	9/1/2006	$1,000,000
HURRICANE ISABEL	9/18/2003	$10,000,000

**Actual dollars when the event occurred.*

In addition, FEMA Disaster Declarations Summary was reviewed to determine past storm events.[170] Counties in HR have declared between 8 to 17 disaster declarations, while cities in HR have declared between 8 to 15 disaster declarations since 1953 (see Figure 35). These numbers may overestimate the total number of storm events as some of these disaster declarations were multiple declarations in the same location for the same storm event, so consider the results somewhat qualitatively.

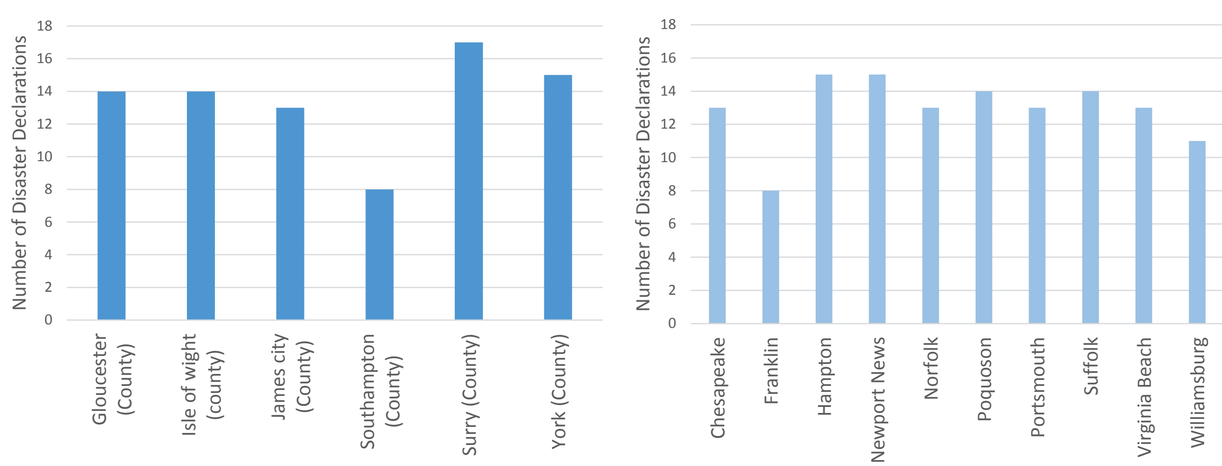


Figure 35. Disaster declarations for the counties and cities in HR since 1953 (Source: data from FEMA Disaster Declarations Summary)

A majority of these extreme weather events were hurricanes/tropical storms followed by winter events (see Table 41). These extreme weather events – notably – did not include heat events or drought. This may suggest that either the HR area has simply not experienced significant heat events or droughts *OR* these events do not cause enough damage to warrant a disaster declaration. Most of these extreme weather events are also consistent with the storms identified using the NOAA Storm Events Database as causing significant damage.

[170] FEMA (2016).

Table 41. Extreme weather that led to FEMA disaster declarations for Hampton Roads (Source: data from FEMA Disaster Declarations Summary; Note date provided in parenthesis is the declaration date not the storm date)

HURRICANES/TROPICAL STORMS	WINTER WEATHER
HURRICANE SANDY (11/3/2012)	Severe storm/flooding (12/9/2009)
HURRICANE IRENE (9/3/2011)	Severe winter storm (2/28/2000)
TROPICAL DEPRESSION ERNESTO (9/22/2006)	Blizzard of 1996 (1/13/1996)
HURRICANE KATRINA (9/19/2005)	Severe Ice Storms (3/10/1994)
HURRICANE ISABEL (9/18/2003)	Severe winter storm (3/25/1993)
HURRICANE FLOYD (9/18/1999)	Severe storms and flooding (11/9/1985)
HURRICANE BONNIE (9/4/1998)	Ice conditions (1/26/1977)
HURRICANE FRAN (9/6/1996)	
TROPICAL STORM AGNES (6/23/1972)	

This collection of information is useful to pull out events that had significant impact in the area and investigate potential impacts on the transportation network. Of those storms that are directly linked to the climate stressors considered in this report (e.g., SLR, storm surge, heavy precipitation), there are 8 storm events that were responsible for substantial damage. A targeted literature review of media records was conducted to identify the storm and present recorded impacts on the transportation system (see Table 42).[171]

Table 42. The weather-related stressors and impacts by historic storm event for HR and Norfolk (Sources: sources used in the table are marked with an asterisk in Appendix B)

EVENT	DATE	STRESSORS	IMPACT
HURRICANE SANDY*	10/28/2012	Hampton Roads: ▪ Very heavy rainfall ▪ Storm surge (high tide about 4 ft above MHHW) ▪ Sustained winds 30-35 mph ▪ Winds at 41 mph recorded at Langley ▪ Flooding of low lying areas of Poquoson, Hampton and Gloucester (high tide was about four feet above normal)	▪ Downed trees ▪ Power outages ▪ Significant flooding ▪ No major incidents or accidents related to the bad weather ▪ All local bridges and tunnels remained open to traffic except unusually high tides closed one lane in each direction on the James River Bridge
		Norfolk: ▪ High tide and powerful surf ▪ 6.85 ft above MHHW at Sewells Point ▪ 5.68 in of rain at ORF through 8 am 10/30	▪ Significant flooding ▪ Closed Midtown tunnel, evacuated some areas ▪ 61 people in shelters

[171] Additional federal funding programs that may provide damage information related to these storms include the FHWA Emergency Relief Program, FTA Emergency Relief Program, Airport and Airway Trust Fund, and special appropriations to the Federal Railroad Administration and the National Railroad Passenger Corporation. (USDOT FHWA (2014b)).

EVENT	DATE	STRESSORS	IMPACT
HURRICANE IRENE*	8/27/2011	Hampton Roads: ▪ Many jurisdictions received high rainfall totals ranging from 6.23 inches (Newport News) to 11.04 inches (Suffolk) ▪ Winds reached 65 miles per hour (mph). ▪ Storm surge 3.5 to 4.5 ft	▪ Debris and downed trees in Suffolk ▪ Death in Newport News because of downed tree ▪ Flooding
		Norfolk: ▪ 7.5 ft at Sewells Point (weather service) 7.63 ft at Sewells Point (Norfolk) ▪ 4.53 in of rain	▪ Downed trees
NOR'EASTER*	11/12/2009	Hampton Roads: ▪ Storm tide 8.59 ft above MLLW; 6.86 ft above MLLW at Coast Guard pier on York River[172] ▪ Max sustained winds 42 mph ▪ Rainfall: 11.92 in Chesapeake; 11.86 in Hampton; 10.58 in Suffolk; 10.58 in Langley; 9.76 in Newport News; 8.66 in Portsmouth; 8.47 in Norfolk	▪ Property damage: ; $450,000+ Portsmouth; $3.4 million Virginia Beach ▪ Downed trees, debris ▪ Eroded Cape Henry beaches
		Norfolk: ▪ 7.75 ft high water mark Sewells Point ▪ 8.47 in rain	▪ Flooding ▪ Over $25 million in property damage
SUPERCELLS	4/28/2008	Hampton Roads: ▪ 11 tornadoes ▪ 3 were EF-0, 7 were EF-1, one was EF-3 ▪ Winds possibly above 135 mph ▪ Travel velocities from 15 m/s to 23 m/s for EF-3 tornado	▪ 200 people injured ▪ Debris, blown-out windows ▪ 12+ homes destroyed, several hundred damaged ▪ $20 million in property damage
NOR'EASTER	11/22/2006	Hampton Roads: ▪ 50-60 mph winds ▪ 6.8 ft high tide at Sewells Point	▪ Flooded streets, Midtown tunnel closed[11] ▪ Power outages affecting 2,200 customers in Southeast VA ▪ Downed branches and trees
TROPICAL STROM ERNESTO*	9/1/2006	Hampton Roads: ▪ Strong winds, heavy rains, storm surge ▪ 5-8 in of rain ▪ Gusts of 60-70 mph ▪ Tides 4-5 ft above normal ▪ 6+ in of rain	▪ Newport News, Poquoson, Gloucester, Isle of Wight, James City, Surry, and Sussex declared major disaster areas ▪ Flooding ▪ Damaged homes, piers, boats, marinas ▪ 200,000 lost power

[172] Mean Lower Low Water (MLLW) is the average of the lower of the two daily low tides over a 19-year cycle.

HURRICANE ISABEL*	9/18/2003	HAMPTON ROADS: ▪ 61 MPH WINDS AT CBBT ▪ 7.9 FT ABOVE MLLW AT SEWELLS POINT, 5 FT STORM SURGE[15], 5.13 FT ABOVE MHHW AT SEWELLS ▪ 5.62 FT MAX STORM SURGE ▪ SECOND HIGHEST ABSOLUTE WATER LEVEL RECORDED AT SEWELLS POINT ▪ 60 KT SUSTAINED WINDS AT GLOUCESTER POINT ▪ 50 KT SUSTAINED WINDS AT NORFOLK NAS ▪ 5-6 FT STORM SURGE IN HR ▪ CBBT 52 KT SUSTAINED WINDS, 4.78 FT STORM SURGE, 7.53 FT STORM TIDE ▪ 2.5 IN RAIN AT ORF, 4.21 IN AT NAS ▪ 60-70 MPH WINDS	▪ BEACH EROSION ▪ TREES AND POWER LINES DOWN ▪ POWER OUTAGES ▪ UPROOTED TREES ▪ FLOODING ▪ MIDTOWN TUNNEL CLOSED

**Indicates this storm prompted a disaster declaration in at least one city and/or county in HR.*

In addition to this information, VDOT's Safety, Security & Emergency Management Division provided emergency transportation costs related to Hurricane Irene for the Commonwealth of Virginia. This information is a record of project costs and type funded for cleanup and repair. The majority of funds were spent on cleanup/debris (93 percent) (see Table 43). Emergency protective measures, repairing roadway damage, and facilities (e.g., fencing) represent the remaining funds (7 percent). This historical information is useful for including emergency management transportation costs associated with potential events. This information can also be collected for additional storms to formulate high-order emergency transportation costs across storm types. Additional storm-related transportation project costs may be available by reviewing FEMA and FHWA reimbursement records.

Table 43. Transportation project costs for Virginia in the wake of Hurricane Irene (Source: VDOT data)

TYPE	# OF PROJECTS	SUM OF COSTS	% OF TOTAL COSTS
CLEANUP/DEBRIS	62	$17,184,233	93.3%
EMERGENCY PROTECTIVE MEASURES	32	$869,073	4.7%
ROADWAY DAMAGE	22	$338,613	1.8%
FACILITIES	7	$35,842	0.2%
TOTAL	**123**	**$18,427,761**	

1-4-2 Recent Studies Quantifying Costs of Climate-Related Impacts

There are three recent studies in HR that quantify losses associated with SLR and storm surge. These studies consider direct losses due to SLR and flooding across multiple sectors. From the transportation perspective, some of the direct losses estimated by these studies may help inform estimates of potential indirect losses when looking through the lens of indirect impacts associated with the flooding of transportation

As noted in the discussion of economic impact analysis (EIA), estimates of how much adverse climate-related events would cost the economy depend on the share of the specific industry sector—finance, manufacturing, transportation, etc. in the region—in terms of their contribution to the region's GDP. Regional economic impact studies provide a baseline assessment capability for these impacts.

HRPDC Roadways and Property Loss due to SLR

The HRPDC Phase III study of SLR risks in HR has produced an extensive report on the exposure of the HR jurisdictions and their roadway network to SLR risks, and has developed baseline data on the potential economic losses in the region. [173] Appendix D describes the methodology HRPDC used to estimates these values.

Two indicators were used to represent the value of impacts: number of parcels affected by SLR and the total dollar value of improvements on the parcel. Parcels that had any portion included in the vulnerable zone were measured as "intersection" metrics. Parcels for which the centroid (weighted middle of the polygon) was within the vulnerable zone were considered as the inventory of properties that would be significantly impacted by 1-meter of SLR above spring high tide, under all three risk scenarios for exposure—low, middle, and high – to account for uncertainty associated with the elevation data.[174]

The HRPDC has produced cost estimates for potential damages from exposure to SLR risks for HR and Norfolk. Exposure data for the transportation network include an assessment of bridge condition described previously in this report. Because the exposure models do not incorporate the potential risk reduction benefits from any current or planned shoreline protection and flooding mitigation improvements, the exposure risk estimates should be considered baseline estimates for the *"Do Nothing Scenario"* that assumes no improvements in the baseline risks.

The analysis revealed localities that are particularly vulnerable to future SLR, including: Chesapeake, Gloucester County, Hampton, Norfolk, Poquoson, Portsmouth, Virginia Beach, and York County. Within HR, this study found that approximately between 1.4 to 7.5 percent of total roadway miles are exposed to 1 meter of SLR above spring tide (see Table 44). There is a greater potential of total roadways being exposed under the high scenario for Norfolk where between 1.3 to 11.2 percent of total roadway miles may be exposed (see Table 45). The study provides a large collection of inundation maps which illustrates an additional component when considering long-term planning to reduce or mitigate transportation vulnerabilities. If roadways are servicing specific neighborhoods that are particularly vulnerable to SLR – will long-term planning evolve in such a way as to reduce the need for maintaining specific roadways (i.e., since the neighborhood it's servicing has migrated to drier ground) or introduce shoreline protections that remove the potential exposure all

[173] HRPDC (2012).
[174] The scenarios consider varying rates of sea level from the current rate ("low scenario") to 0.5 meters of rise adjusted to reflect historic trends at local tide gages ("medium scenario") and 1.5 meters of rise adjusted to reflect historic trends at local tide gages ("high scenario").

together. For example, Norfolk may be greatly affected by SLR. Currently, the SHELDUS records suggested $116M of property damage from the flooding events in Norfolk for the 1960-2014 period. Under future SLR conditions, the HRPDC Phase III study identified over $350M of real estate in Norfolk where the centroid of the property was in the one-meter sea-level rise flood zone, and over $1.7B of real estate in Norfolk where there is at least some portion of the property in the one-meter sea-level rise flood zone.[175] If future planning builds in protection mechanisms for these properties, this may also reduce roadway flooding.

Table 44. Exposure to one meter SLR above spring high tide in Hampton Roads (Source: HRPDC (2012))

EXPOSURE	TOTAL	LOW RISK ESTIMATE	MIDDLE RISK ESTIMATE	HIGH RISK ESTIMATE
LAND AREA (SQ. MILE)	2,948	171	238	311
POPULATION	1,666,310	59,59	112,794	176,124
HOUSING UNITS	677,49	24,436	45,791	71,548
# PARCELS (INTERSECTION)	605,284	39,564	61,254	84,780
# PARCELS (CENTROID)	605,284	16,000	35,654	58,651
IMPROVEMENT VALUE (INTERSECTION)	$128,305,696,321	$20,328,915,919	$26,161,421,399	$30,833,003,959
IMPROVEMENT VALUE (CENTROID)	$128,305,696,321	$4,142,308,080	$8,766,633,550	$13,410,140,979
TOTAL ROAD MILES	**11,676**	**161.5**	**507**	**877**
INTERSTATE	**250**	**5.7**	**14**	**18**
PRIMARY ROADS	**1460**	**17**	**50**	**77**
SECONDARY ROADS	**2216**	**24**	**72**	**98**
LOCAL/PRIVATE ROADS	**7840**	**114.7**	**371**	**684**
# BUSINESSES	57,579	575	2026	3,659
# EMPLOYEES	719,835	5,237	25,088	50,869
TOTAL VALUE OF PARCEL (INTERSECTION)	$215,436,678,988	$38,892,731,860	$48,067,888,230	$56,306,819,672
TOTAL VALUE PARCEL (CENTROID)	$215,436,678,988	$8,513,744,141	$16,466,833,462	$25,104,125,807

175 HRPDC considers these as conservative estimates that take into account uncertainties associated with the accuracy of the elevation data. It should be noted that the SHELDUS data are retrospective estimates based on actual damages, while the HRPDC damage estimates relate to the value of the assets in the flood zone at risk of potential damage.

Table 45. Exposure to one meter SLR above spring high tide in Norfolk (Source: HRPDC (2012))

EXPOSURE	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
LAND AREA (SQ. MILE)	56	3.1	6.5	9.2
POPULATION	242,803	9841	25,715	36,134
HOUSING UNITS	95,018	3502	8,955	12,896
# PARCELS (INTERSECTION)	65,979	4,555	8,251	11,567
# PARCELS (CENTROID)	65,979	1,757	4,968	8,204
IMPROVEMENT VALUE (INTERSECTION)	$13,494,681,500	$1,703,705,500	$3,207,444,200	$3,917,995,600
IMPROVEMENT VALUE (CENTROID)	$13,494,681,500	$350,808,300	$1,325,957,300	$2,234,621,300
TOTAL ROAD MILES	**1,150**	**15**	**76**	**129**
INTERSTATE	**55**	**1.7**	**5**	**7**
PRIMARY ROADS	**152**	**1.0**	**9**	**13**
SECONDARY ROADS	**0.0**	**0.0**	**0.0**	**0.0**
LOCAL/PRIVATE ROADS	**943**	**12**	**61**	**109**
# BUSINESSES	9,118	111	532	946
# EMPLOYEES	136,292	1,924	9,818	15,014
TOTAL VALUE PARCEL (INTERSECTION)	$20,670,093,500	$3,189,941,400	$5,357,247,300	$6,485,310,600
TOTAL VALUE PARCEL (CENTROID)	$20,670,093,500	$627,145,700	$2,225,096,200	$3,860,392,700

Table 46 below summarizes the monetized values, derived from Tables 44 and 45 for the assets at potential risk of SLR and flooding for assets located in the HR region and Norfolk. The dollar loss values reflect the valuation of the potentially exposed developed land and property parcels for Mid-level SLR risks (based on the risk scenarios for exposure to 1 meter (3.3 feet) SLR above Spring High Tide.)[176] The table underscores the greater vulnerability of Norfolk compared to the HR region as a whole: Norfolk faces the potential loss of approximately 10 percent of its assets (value between $1.3B and $2.2B) compared to the regional exposure levels of about 7 percent of the properties.

Table 46. Potential asset loss for Norfolk and HR properties from exposure to SLR risks (Source: HRPDC (2012))

ASSET LOSS MEASURES (MID-LEVEL EXPOSURE RISK)	NORFOLK POTENTIAL $ LOSS VALUE (% TOTAL ASSETS)	HR REGION POTENTIAL $ LOSS VALUE (% TOTAL ASSETS)
IMPROVEMENT VALUE (CENTROID)	$1.3 B (9.6%)	$8.8 B (6.9%)
TOTAL VALUE OF PARCEL (CENTROID)	$2.2B (10.6%)	$16.5B (7.7%)

[176] Note that the differential influence of "intersection" and "centroid" is reflected in estimates of loss values for the three Low, Middle, and High scenarios (but the values are reported as equal for both rows).

Estimating Transportation Exposure and Business Losses due to Flooding in Norfolk

A recent study examined flood risks to electrical power, telecommunications, transportation fuels, and transportation under a 100-year flood scenario (i.e., an event that has a 1 percent chance of occurring in any given year possibly caused by a hurricane or nor'easter) under three sea level rise scenarios, including an increase of +0 feet (i.e., today's conditions), +1.5 feet, and +3 feet.[177] The analysis illustrated which assets within these sectors were potentially exposed to flooding (see Figure 36). In addition, the study used the Regional Economic Accounting (REAcct) Tool to estimate the regional and national economic impacts associated with the flood event under various SLR scenarios over a four-day period. REAcct is an Input-Output (I-O) model that provides regional or county-level estimates of direct and indirect impacts of the firms whose businesses have been adversely impacted by the disruption. The tool has a two-prong approach: (1) calculates the number of employees directly impacted by the event through GIS analysis, and (2) estimates the indirect impacts on the region's firms.[178] Indirect impacts are calculated by applying Regional Industrial Multiplier System (RIMS) II Input-Output multipliers which "are ratios of the total change to the initial change in regional economic activity."[179]

[177] Sandia National Laboratories (2016).
[178] Sandia National Laboratories (2011).
[179] Bureau of Economic Analysis (2013).

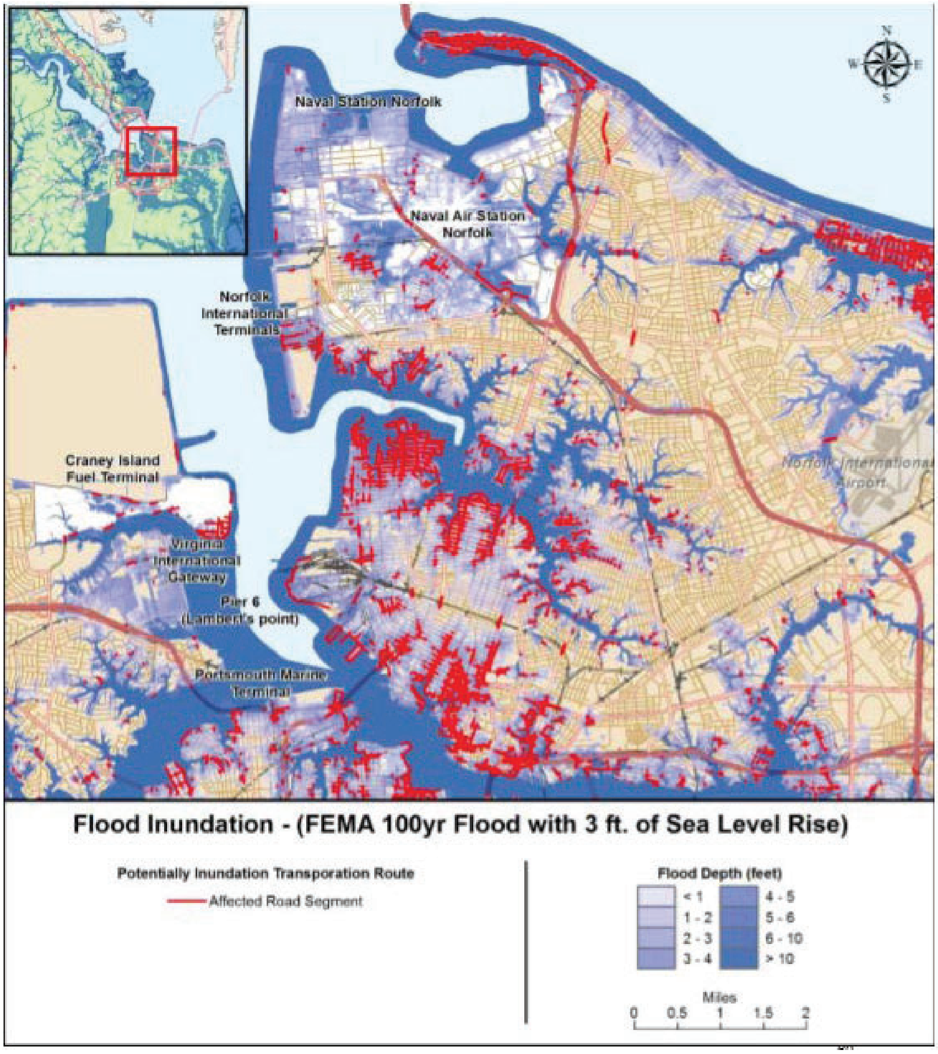


Figure 36. Transportation paths impacted by flooding with overlay of +3ft scenario (Source: Sandia National Laboratories (2013))

This analysis found the transportation sector being strongly at risk to potential flooding. From the exposure portion of this analysis, five of the nine major bridges and tunnels in HR were identified at a high flood risk to the 100-year flood (see Table 47).

Table 47. Major bridges and tunnels in Hampton Roads with anticipated risk of closure due to the 100-year flood (Source: Sandia National Laboratories (2011))

Bridge Name	Route	City/County From	City/County To	Expected Flood Risk
Hampton Roads Bridge Tunnel	I-64	Norfolk, VA	Hampton, VA	High
Monitor Merrimac Bridge Tunnel	I-664	Suffolk, VA	Newport News, VA	High
Berkeley Bridge and Downtown Tunnel	I-264	Norfolk, VA	Norfolk, VA	High
South Norfolk Jordan Bridge	Rte. 337	Chesapeake, VA	Portsmouth, VA	Med
Midtown Tunnel	Rte. 58	Norfolk, VA	Portsmouth, VA	High
High Rise Bridge	I-64	Chesapeake, VA	Chesapeake, VA	Med
Gilmerton Bridge	Rts. 460, 13	Chesapeake, VA	Chesapeake, VA	Low
Chesapeake Bay Bridge Tunnel	Rte. 13	Virginia Beach, VA	Kiptopeke, VA	High
Norfolk Southern Railroad Bridge	NS Rail	Norfolk, VA	Norfolk, VA	Med

Specifically:

- Roadways/Highways:
    - Two bridge-tunnels that provide access to the Virginia Peninsula (between northern and southern HR) are at high risk for closure under all future scenarios. A possible alternative route could be over the James River Bridge on Route 17/Route 32 which has a lower risk level.
    - Not only were coastal roadways at risk to flooding but so were inland roadways, particularly ones in Western Norfolk and along Elizabeth River. These flooding situations can create choke points and hot spots for travelers.
    - Bridges over Elizabeth or Lafayette rivers may be closed largely cutting-off travelers to/from downtown Norfolk and around Old Dominion University.

- Rail line:
    - Much of the Norfolk Southern rail line is not at risk for flooding except the crossing of the Elizabeth River.
    - Possible flooding where the rail line at points where it crosses Wayne Creek, Gilligan Creek, and Elizabeth River.

- Ports and Piers:
    - Intensive flooding of western Norfolk Peninsula affecting the use of Lambert Point's Coal Terminal.
    - Roadways within the Norfolk International Terminal (NIT) facility to the south and west of the rail line are at risk for flooding.

Hampton Roads. Industry losses for HR were estimated as a consequence of the disruption to electrical power, telecommunications, transportation fuels, and transportation. Figure 37 shows estimates of direct losses of the top 5 industries in HR as a consequence of a 4-day business disruption for three exposure scenarios for SLR (0 feet, 1.5 feet, 3 feet) combined with the 100 year flood. In the Professional/Technical sector, for instance, the region's direct losses would range between $34M and $58M depending on the storm intensity scenario.

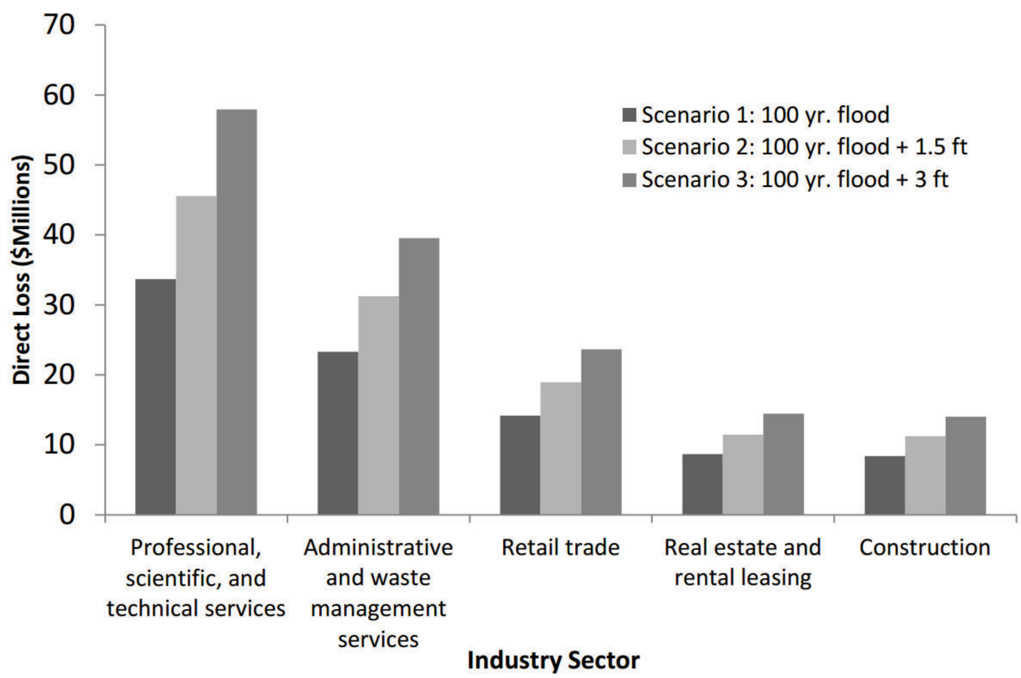


Figure 37. Top 5 direct losses in HR, as a consequence of a four day business interruption under three exposure scenarios (Source: Sandia National Laboratories (2011))

Norfolk. Total potential business losses in Norfolk, i.e. direct and indirect, were also estimated for the 4-day disruption. Potential direct losses ranged between $27M and $56M, depending on scenario (see Figure 38). The direct cost, however, accounted for only 38% of the total losses. When indirect costs - incurred by an array of economic costs due to business interruption, loss of the means of livelihood and access to job and mobility - were added to direct property losses, the total losses from direct and indirect damages rose by a factor of 2.6, with a range between $70M and $144.6 M, as summarized in Table 48. Indirect costs were estimated using the Regional Industrial Multiplier System (RIMS II).

Table 48. Estimates of direct and indirect losses in Norfolk for a four day business interruption under three scenarios (Source: Sandia National Laboratories (2011))

	Scenario 1	Scenario 2	Scenario 3
Annual Direct Losses	$26.92M	$39.71M	$55.60M
Annual Indirect Losses	$43.08M	$63.49M	$89.00M
Total	**$70.0M**	**$103.2M**	**$144.60M**

Comparing Norfolk with four other HR jurisdictions, Virginia Beach has the greatest direct loss associated with business disruption followed by Norfolk (see Figure 38). This suggests these two jurisdictions may be at greatest risk during flood events, which may then be further exacerbated by SLR.

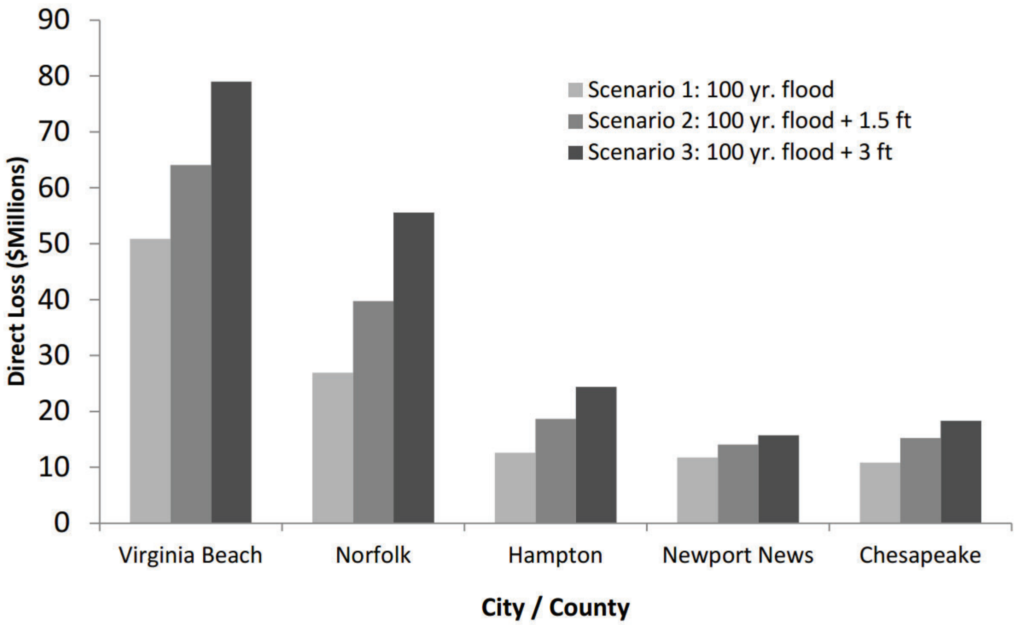


Figure 38. Top five HR cities ranked by direct losses due to four days of disruption (Source: Sandia National Laboratories (2011))

Military Sector

The implications of the changes in DOD spending and employment on current and potential future economic conditions in HR, and in Norfolk in particular, have been examined in Sandia's study of the economic impacts of SLR. The Sandia study underscored the extent to which the Norfolk's economy is intertwined with the Naval Station, noting that the Naval Station's functions play a key role in the regional economy, generating a significant multiplier effect in additional jobs and revenues. Implementing adaptation projects in Norfolk to mitigate the SLR and flooding risks, the report concluded, will have beneficial impacts beyond protecting the Norfolk International Terminal (NIT) container shipping operations (see textbox).

> *Norfolk operates as a major cog in the Hampton Road's port machine. Because of this, protecting Norfolk from flooding will protect approximately half of Hampton Road's coal shipping capacity, half of its container shipping capacity… Norfolk is innately intertwined with successful operation of NAVSTA Norfolk and supporting facilities… Norfolk's flooding resilience will have an impact to the individuals that work and serve at these facilities, as well as the facilities themselves.*
>
> Source: Sandia National Laboratory (2016).

As for the role of the region's transportation network on the military facilities' exposure to risk, the HRPDC 2034 Long Range Transportation Plan (LRTP) has identified six key locations in the Norfolk network of highway

tunnels and bridges that represent significant traffic delays and capacity constraints for military operations.[180] These six Norfolk-area military facility capacity problem areas were: [181]

- The I-564 Inter modal connector;
- The Air Terminal Interchange;
- South Norfolk Jordan Bridge;
- Midtown Tunnel;
- Improved Harbor Crossing (with Third Crossing);
- I-64 Corridor Expansion.

1-5 DATA ON ADAPTATION IN HR

There are multiple planning avenues for considering adaptive strategies, including key strategies that reduce the impacts, and those that mitigate the consequences (see Figure 39). Such strategies can be introduced at many entry points of an assets lifetime such as during the planning, procurement process, design, construction, maintenance, repair, and operations. A number of metrics can be considered when weighing which adaptive strategies may be best such as economic costs, environmental consequences, social justice issues, etc. This section considers past efforts in HR for quantifying the economic costs and benefits associated with adaptive strategies for various purposes. This information provides invaluable dollar estimates of potential strategies relevant to the region.

[180] The report also stressed the need to extend the Light Rail extension to Naval Station Norfolk, and the need for high-speed intercity passenger rail service connecting HR to Richmond, DC, and beyond, since having the ability to conduct travel to key regional points by rail (and conduct a full day's business in DC without an overnight stay) yield substantial cost saving benefits.
[181] HRTPO (2012a).

Role of Adaptive Strategies in Reducing Impacts and Consequences

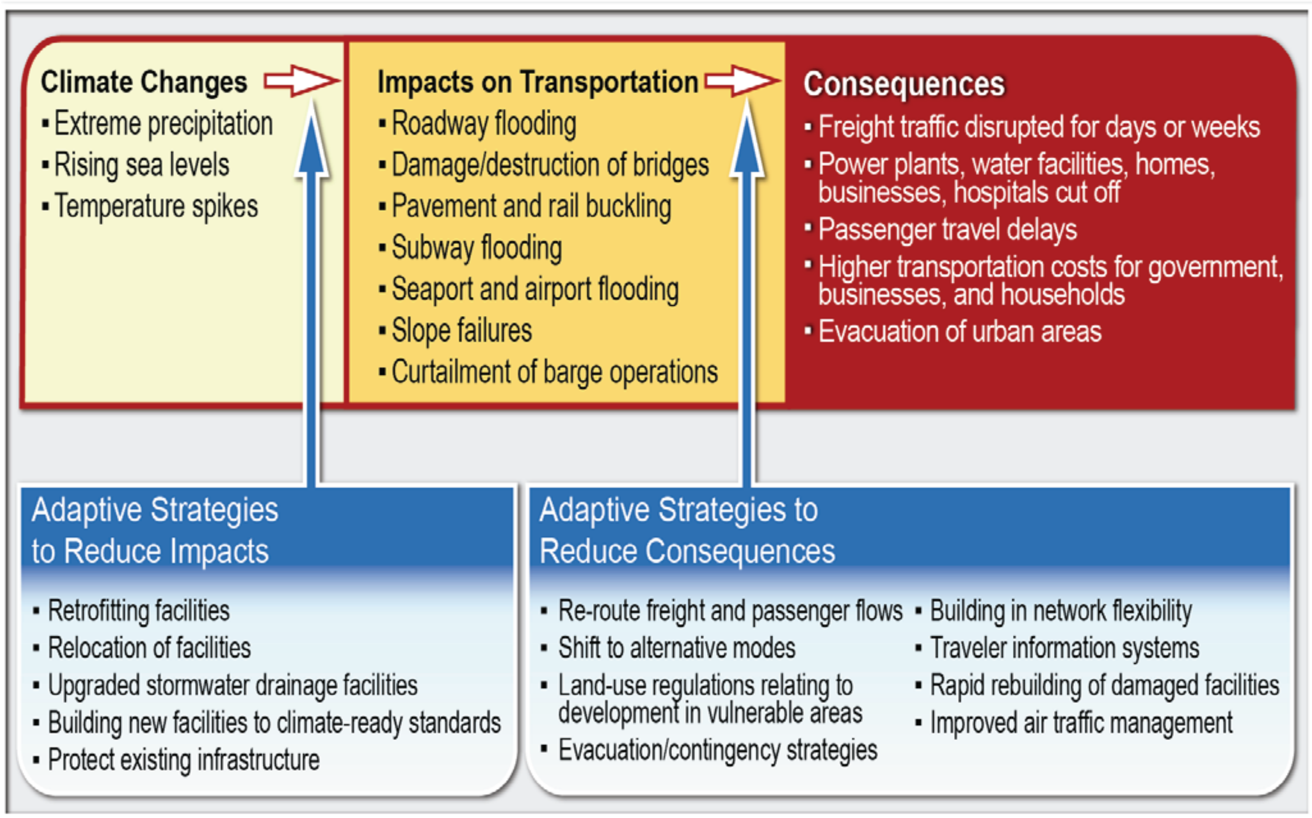


Figure 39. USGCRP view of climate change adaptation components (Source: U.S. Global Change Research Program (USGCRP) (2009))

"Buying Down" Flood Risk

One example of the risk-reduction strategy is the USACE's promotion of the concept of "buying down" a region's flooding risks. The strategy consists of a systematic process for reducing flood risks that includes: calculating the difference in the magnitude of the estimated costs of *Initial Risk* and the remaining *Residual Risk,* by quantifying the cumulative impact of the adaptation measures implemented. The table below describes the 6 of the 8 components of the process for assessing risks and vulnerabilities, calculating the consequences of each measure, and then, more effectively dealing with the diminished residual risks of the region flooding, depicted as the 6th component of the risk-buying down process. It should be noted that the contribution of insurance to mitigating flooding risks represents only a transfer of damage costs, and to this extent would overestimate the total cost-saving benefits.

Example of mitigation and adaptation actions for USACE defined risk and reduction tools

Risk Components	Mitigation and Adaptation Actions
1 – *Initial Risk*	Inventory of existing conditions and vulnerabilities: fragile levees, erosion of system design standards, aging infrastructure, underfunded maintenance projects, environmental threats, urbanization
2 – *Zoning*	Flood plans and zoning, 200-year flood plans for minimum protection for urban areas, amendments to zoning ordinances, shared liability of state and localities, designation of floodways
2 – *Building Codes*	New building standards, incorporation of climate change/SLR into codes and standards
5 – *Insurance*	Flood plain mapping, annual flood risk notification
6 – *Non-Structural*	Home relocation, raising or buyouts (reduce flood damage)
7 – Structural	Beachfill or breach contingency plans (reduce flood impact)
8 – *Residual Risk*	Financials costs and consequences of damages

Source: USACE (n.d.).

1-5-1 Existing Adaptation Measures for City of Norfolk

Norfolk prepared a report on Coastal Resilience Strategy,[182] a report that documented the existing adaptation measures, including the plans for a half-mile long floodwall in downtown Norfolk with five tide-gates and a pump station for draining runoffs. The City planning projects include these structural projects:

- Raising road on Brambleton Avenue to allow improved access by raising the roadway to nearby medical complex ($2.4M);
- Building flood walls, earthen berms, gates, pumps and elevating electricity structures (potentially underway, with costs estimated between of $10M to $306M);
- The USACE conducted a study of the OceanView beaches to inform Norfolk's flooding plan, resulting in a proposal of Norfolk's first "*engineered beach*" (with the estimated construction cost of $18.4M with a city share of $5.5M; accounting for 30 percent of total costs);
- The USACE study of The Hague and Pretty Lake projects for SLR and flooding protection, where the agency will pay for a large portion of the costs.[183]

Identifying the need for adaptive strategies

Coastal Resilience Index, developed by Mississippi-Alabama Sea Grant Consortium and NOAA's Coastal Storms Program, helps a community self-evaluate how prepared it is for coastal hazards from extreme events. The index is calculated based on stakeholder responses to an 8-page self-assessment tool of predominantly yes/no questions. The goal of this effort is to enhance effective communication within communities and identify any gaps in preparedness. This tool may prove useful in identifying potential adaptive strategies.

1-5-2 Flood Mitigation for City of Norfolk

The engineering firm Fugro has also completed a flood mitigation study for Norfolk. The study involved installing and monitoring new long-term tide gauges, developing a GIS platform for a flood model, conducting coastal engineering evaluations to define flood exposure and prioritize projects, and developing an interactive predictive flood impact model. The study included five structural adaptation projects for building:

- A floodwall to protect against tidal surge;
- Tide gates for navigation access;
- A pump station to remove rainfall runoffs;
- Berms and closure walls to protect against low watershed perimeter;
- Raised roads as protection against flooding.

[182] Norfolk, City of (n.d.).
[183]Other estimates of adaptation costs: Wetlands Watch reports that the Norfolk Naval Station has been spending an estimated $35M to $40M to replace piers vulnerable to inundation. The Naval Air Station Oceana in Virginia Beach and Dam-Neck Annex are also reported to be threatened by SLR "encroachment", as it was previously by the encroaching residential developments threatening its move.

The Fugro plan focused on four areas within Norfolk: Mason Creek, Pretty Lake, The Hague, and Ohio Creek. The engineering area of focus represents only 18 percent of the size of the city, but includes 16,126 structures, 14,993 of which are residential. Two of the three neighborhoods in the study, The Hague and Pretty Lake, contain about 9,000 structures. The study recommended a capital project to protect Pretty Lake against coastal flooding and runoff, including: construction of a tidal barrier to protect against surge; a tide gate to preserve navigation; a pump station to remove rainfall when the gate is closed; and raised roads where the land surface is too low around the watershed perimeter. Norfolk's low-income neighborhood of the 1970s-era townhomes was hit by extensive flood damage several times. The City Council members have advocated buying out and razing the structures. The Fugro study recommended a three-phase approach for at-risk neighborhoods:

- Phase 1: the buyout of the most vulnerable properties;
- Phase 2: installing a pump station to reduce rainfall impact during tidal surge; and
- Phase 3: installing a box culvert to improve the drainage system.

The four project areas were as follows:

- Hague Flood Wall – preliminary design completed; estimated costs $60M.
- Pretty Lake Flood Wall – preliminary design; estimated cost: $50M;
- Mason Creek Pump Station – cost: $30M;[184]
- Ohio Creek (also known as Spartan Village) – for improvements in a tidal area that has been most at risk from repetitive flooding.

The total adaptation costs for three of the above projects in the Fugro study were estimated at $140M. The engineering firm also estimated the benefit-cost ratio for some of the projects is as high as 2:1.[185] By one estimate, the capital costs for the three projects account for 2.8% of the assessed value of the properties in the three Norfolk neighborhoods (not including the Ohio Creek project), as summarized in Table 49.[186]

[184] This is a capital project intended to protect against rainfall runoff (area protected from tidal surge by an existing Tidal Gate (operated by the Navy) that will require: a pump station to remove rainfall runoff when gate is closed; a new storm culvert beneath the Navy berms and peripheral wall when land surface is low around creek; involves street elevating and future improvements).

[185] Although the city currently has a city-wide freeboard requirement of 1 foot, they are looking at increasing it. Norfolk was the earliest jurisdiction in HR to reference the issue of SLR. The city is taking on a number of projects that will increase its resilience, including creating a living shoreline along Haven Creek and making drainage improvements. In addition, the city is replacing and elevating a bulkhead 1.5 to 2 feet above the existing bulkhead at a cost of $440k, as well as installing a mobile pump to deal with tidal flooding.

[186] In Norfolk alone, a consultant has identified $1B in Protection improvements on the Lafayette Watershed in floodgates, berms and drainage improvements. (Source: VA Chamber Foundation (2015)).

Table 49. Proposed Norfolk flood control engineering projects (Sources: Norfolk, City of (2012a), Norfolk, City of (2012b))

CITY OF NORFOLK NEIGHBORHOOD	PROPOSED ADAPTATION AND MITIGATION PROJECTS	ASSESSED PROPERTY VALUE IN THE WATERSHED	ESTIMATED COST	PROJECT COST AS % OF PROPERTY VALUE
THE HAGUE	• Floodwall • Tide gate • Pump Station • Berms/Closure walls	$1,624 M	$60 M	3.7%
PRETTY LAKE	• Floodwall • Tide Gate • Pump Station • Structure elevation	$1,812 M	$50 M	2.8%
MASON CREEK	• Pump Station • New storm culvert • Peripheral Berms • Structure elevation	$1,604 M	$30 M	1.9%
TOTAL	NA	$5,040 M	$140M	2.8%

Evaluating Drainage Projects in The City of Norfolk

The *2012 City-Wide Drainage Study* identified a total of 253 drainage projects, and evaluated flooding risks caused by rain. The scoring and prioritization criteria were based on the following eight criteria in as shown in the Table below. The findings suggest that about 150 miles of roadway need some form of drainage and roadway improvements, costing $561.6M. These improvements do not include possible utility improvement projects, pumps stations or outfall improvements.

Prioritization criteria for Norfolk city-wide drainage study. (Source: Norfolk, City of (2012))

Prioritization Criteria	Maximum Score
Identified complaints/flooding events + maintenance needs	30
Location of completed/planned CIP project	20
Existing infrastructure capacity per acre of developed area	20
Portion of the drainage designated to pass a 10-year storm (those not passing were assigned a higher #)	15
Infrastructure condition (those with poor condition got a higher score)	15
Road classification (winter vehicular moves and ER/evacuation impacts)	15
Critical infrastructure (fire, police, hospitals, etc. get a higher ranking)	15
Presence of Business Development Focus Area	10

Source: Norfolk, City of (2012c).

1-5-3 Hampton Boulevard Corridor

Another study on the Norfolk SLR adaptation projects is the case study of the Hampton Boulevard Corridor.[187] Hampton Boulevard starts along Norfolk Naval Station and leads to the Midtown Tunnel. The Port Authority Police and Old Dominion University are also located along this residential route. The Boulevard is near the coastal Lafayette and Elizabeth Rivers, making it vulnerable to flooding, even absent rain events, when high tides range from 2 to 8 feet, disrupting traffic along the road for an extended period of time. The study team developed estimates of project cost and type, including:

- **Flood barriers between Craney Island and Port Authority**. Estimated cost of the 1.53-mile structure is $2B. The design of this project replicates the Maeslantkering Barrier in the Netherlands, a structure that is machine operated, equipped with sensors that would provide warning of the tidal rise at Sewells Point, automatically signaling the need for the barrier to close at the anticipated SLR, when the gates are closing, the barrier floats until it is securely closed, then sinks into place where it will block the surge of high tide. The gate will stay open to navigation during normal tide conditions. The project will require construction of man-made islands on either sides. The project costs are high relative to smaller alternative projects and would require extensive maintenance.

- **Bioretension Basin Rain Garden System**. This is a system that works by directing the storm water to the basin, where it percolates through the rain garden and is treated through biochemical and natural process. The treated water then infiltrates and is directed to nearby storm-water drainage, directing the water away from vulnerable infrastructure. By slowing down the runoff, the basin relocates the storm water, purifies it to reduce the nitrogen and phosphorous levels of the storm water and sediments. Currently, one project in Norfolk, the Blue Bird Park Stormwater Wetland Construction project, at an estimated cost of $84,500, is currently in the development stage. Also, Myrtle Park Wetland restoration project is underway. Together these projects will be effective in redirecting some of the storm water. The City is currently pursuing a policy of encouraging residents along the Boulevard to construct rain gardens on their property to help prevent straining the drainage system capacity and extend the projects' life span.

- **The Lafayette River Flood Wall.** This project is designed to protect homes along the end of the river without destroying the area's natural beauty. The proposed Wall ranges from 3 to 10 feet in height and cost $110 to $400 per feet in length. The Wall's engineering requirements are stringent, given the need to prevent seepage of water through assembled segments.

- **A Flap-type Flood Barrier operated by a Hydraulic Cylinder.** This barrier lies flat on the seabed beneath the Hampton Boulevard Bridge, and will rise up to block the excess inflow of water when a storm surge or high-tide is predicted. The barriers will control the fluctuation of water levels when it is elevated. The barrier's design is similar to the Thames River Barrier in U.K. and the Stamford

[187] University of Virginia (2015).

Hurricane Barrier in Connecticut. (The project costs are expected to be less than the more elaborate Craney Island Barrier.)

Protecting Against SLR: Adaptation Costs

NOAA's evaluation template for protecting against SLR contains five types of adaptation:

1. *Managed Retreat*: transfer of development rights; purchase of rights; relocation;
2. *Tidal Management*: storm surge barriers;
3. *Engineered Barriers*: levees and dikes; sea-walls; beach nourishment; sand bagging;
4. *Infrastructure Modification and Design*: elevated development; flood-proofing facilities; floodable developments; floating developments; movable structures;
5. *Land-Use Policy and Zoning.*

Example of generic cost ranges for Tidal Management and Engineered Adaptation Options:

- *Storm-Surge Barriers*: can be a fixed structure (e.g., a closure dam) that is permanently closed, or movable gates or barriers that can be opened and shut. These are high cost: from $0.7M to $3.5M per meter, plus annual maintenance; effective in reducing the surge; downside: potential environmental and waterway damage;
- *Beach Nourishment*: costs: $300-$1,000 per foot;
- *Seawalls*: $150-$4,000 per linear foot;
- *Levees and Dikes*: $100-$1500 per foot;
- *Engineered Developments*:
  - Elevated structures: $2,000-$30,000;
  - Floating developments: $2,000-$30,000;
  - Floatable developments: can be cost effectively implemented during design/construction;
  - Drainage systems: costs vary;
  - Flood proofing: can be cost effective and implemented as part of the design/construction.

Source: NOAA (2013).

Example: Adaptation in NYC

ClimAID produced the following adaptation solutions for New York City:

- Seal ventilation street grates for subway systems in flood zones, and replace passive open ventilation with forced closed vents;
- Install flood gates at vulnerable entrances;
- Build berms and levees;
- Update flood maps to show flood elevation for 100- and 500-year recurrences and add projections on SLR;
- Implement design and retrofit transportation infrastructures for adaptive resilience;
- Update emergency response plans;
- Alternative plans, including barriers to protect the entire New York harbor and estuary, similar to London's Thames barriers.

Post-Sandy damage evaluations demonstrated the high effectiveness levels for two adaptation measures:

- Temporary barriers at the Harlem River Tunnel prevented flooding of subway lines between Manhattan and the Bronx;
- Removing sensitive signal and control systems from most tunnels expected to be flooded, and reinstalling them after the storm—proved highly effective in keeping signals free of damage from salt water, saving one or two weeks of recovery time and an estimated $10B in damages.

Source: New York State Energy Research and Development Authority (2011).

1-6 CHALLENGES WITH QUANTIFYING COST BURDENS

1-6-1 Challenges with Economic Loss Associated with Recurrent Flooding

A major consequence of recurrent flooding is that many damages remain unpaid, which in turn makes it harder to quantify the cost burden of extreme weather events and determine the full extent of the needed adaptation measures. In 2009, Norfolk reported 280 "frequently flooded" or "repetitive-loss properties" that needed some form of flood mitigation. The National Flood Insurance Program (NFIP) has defined "repetitive losses" as "properties that have experienced at least two paid flood losses of >$1000 each in any 10-year period since 1978." In the 2013-2014 period, the repetitive loss estimate in Norfolk had risen to 900 structures, more than a threefold increase. In addition to Norfolk, four other HR cities were reported to have experienced a total of 2,979 repetitive property losses which were not compensated by private insurance or NFIP. Together these repetitive property-damage events incurred a total of $431M in uncompensated costs, creating a large gap between what FEMA paid and what was needed for flood mitigation improvements. FEMA, under its Hazard Mitigation Assessment (HMA) program, provides post-hazard grants to states/localities

through a competitive process.[188] The FEMA HMA funds have not kept pace with the increased rate of flood damage. The FEMA HMA funds only apply to the insured structures, and do not cover costs of roads and transportation infrastructure mitigation projects, which need to be funded by other funds (if at all), typically out of the local government's Capital Improvement Plan (CIP), transportation improvement plan (TIP), or storm water funding. Virginia's Revolving Fund (for water, dam safety, and clean water), and more recently, Green Bonds,[189] have historically been used to pay for these damages. Table 50 shows the scale of repetitive-loss properties, and the gap between the needed mitigation funds and the compensations paid by FEMA, in Norfolk and four other HR cities.[190]

Table 50. 2013-2014 property loss data on repetitive loss properties (Source: Wetlands Watch (n.d.))

HR CITY	# OF REPETITIVE LOSS PROPERTIES	AVERAGE COST OF MITIGATION (000)	TOTAL COST OF MITIGATION (000)	AVERAGE FEMA FUNDING
CHESAPEAKE	409	$250	$102,250	$757K
HAMPTON	863	$75*	$64,725	$833K
NORFOLK	900	$162.5	$146,250	$778K
PORTSMOUTH	186	$75	$13,950	$NA
VIRGINIA BEACH	561	$185	$103,785	$725K
TOTAL HR	**2,979**	**NA**	**$430,900**	**NA**

**Average statewide mitigation cost of $75,000 was used for localities where data were not available.*
Figures do not include unclaimed damages.

1-6-2 Private Insurance

Compounding the role of uncompensated repetitive flood damages, and high levels of economic disadvantage, is the availability of insurance. Because of the public-goods character of much of infrastructure systems in HR exposed to SLR and flooding risks, it is often difficult to assign property rights and responsibility for paying for the damage costs. Though the insurance industry provides a substantial contribution to rebuilding after an extreme storm, in some instances, the government and the public may incur a greater amount of the cost burden. For example, a recent National Resources Defense Council (NRDC) paper has maintained that in the aftermath of the 2012 Hurricane Sandy the common claim by the insurance industry was that the major share of the damages—at a total cost of $139 billion, considered the 2nd costliest climate disaster in the U.S.—was paid for by private insurance.[191] However, the researchers found that the private insurance payout amounted to only $33 billion (24%), with the largest share, $96B (69%), paid out of the public coffers, as Table 51 shows.

[188] The FEMA HMA grant program covers installation costs of flood vents, elevating utilities, elevating structures, and outright purchase of property.
[189] Green Bonds are bond whose proceeds fund environmentally friendly projects. They were first issued by World Bank, but now many banks and governments issue them. Vienna was the first local government in Virginia to issue Green Bonds, in 2015.
[190] Wetlands Watch, (n.d.); The uncompensated-loss estimate was based on applying an average loss estimate of $143,700 per property. The report points out that FEMA's NFIP premiums have been scheduled to rise (effective 2013) in all Virginia coastal areas. The report estimates that it would take FEMA between 78 and 188 years to clear the backlog of flood damage improvement needs.
[191] NRDC (2013).

Table 51. Allocation of the 2012 Hurricane Sandy cost burden (Source: NRDC (2013))

SOURCE OF PAYMENT	COST BURDEN ($BILLIONS)	% SHARE
PRIVATE INSURERS	$33	24%
US TAX PAYERS	$96	69%
UNINSURED	$10	7%
TOTAL STORM-RELATED COSTS	**$139**	**100%**

This type of analysis is important when considering who will incur the cost burden in the aftermath of an extreme weather event (e.g., is it the same parties that pay for an adaptive strategy that reduces harm and associated costs).

How do Private Insurers Measure Risk?

Risk is the difference between expected outcomes and potential outcomes. The expected loss is calculated by multiplying the probability of an outcome by the cost of that outcome, and summing all the multiples. Then the standard deviation is calculated to measure the potential variability. The greater the variability, the greater the risk.

For example, an insurance company might consider the potential costs of flood damage associated with varying levels of flood (e.g., nuisance flood, 20-year flood, 50-year flood, 100-year flood). The potential costs of flood damage for varying levels of flood can be calculated by first determining the likelihood of whether the home will flood (e.g., is the home is located in a flood-prone area as illustrated by FEMA's Flood Insurance Rate Maps (FIRM)). Then, determining the consequence if a flood were to happen using FEMA's depth-damage curves for the type of house (e.g., a graph that shows the depth of the flood water from 0 to 10 feet and the associated costs of damage that may be incurred for a one story home without a basement). The insurer may then determine the average flood damage that may occur over a window of time. The more individuals living along the coastline from the Gulf Coast through the Atlantic that can be insured, the greater the reduction of the insurers risk. For example, if a storm were to occur, it is assumed only a portion of the insured collection of homes would be damaged.

For additional insight on how private insurance view risk of flooding events, see Appendix E.

Source: Anderson et al. (2005); Per communication with Mr. Steve Kolk, Assistant Vice President of Pricing American Integrity Insurance Group.

PART 2 – OVERVIEW OF ECONOMIC METHODOLOGIES AND ASSESSMENT RESOURCES

There are a number of pathways to consider when quantifying the direct and indirect economic costs associated with transportation climate resilience. This discussion considers the direct and indirect costs of an extreme event and the direct and indirect costs and benefits of adaptive measures.

The direct and indirect costs of the event, in the "business as usual" case, includes the consequences of a severe weather event such as repairing damage to transportation infrastructure, associated fatalities and injuries, which have relatively straightforward methods for their calculation. Consequences can also include related effects such as traffic delays or less-tangible effects such as environmental or quality of life degradation.

The direct and indirect costs and benefits of, in essence, protecting a community against the impacts of a catastrophic event on transportation infrastructure ("adaptive strategies" or "alternatives") may be considered at various entry points, which are prior to the anticipated threat occurring (including short-term and long-term planning), during the exposure to the threat, or soon after the threat has occurred. For example, tangible costs incurred due to storm surge of an event could include fatalities and injuries and traffic delays while intangible costs might be the loss of environmental services or degradation of quality of life. There are a number of economic analyses to choose from when considering transportation investments involving adaptive strategies for coping with the impacts of climate change. It's important to note that in some instances, the proposed adaptive measures may be cost-effective even without considering climate change.[192] These measures may be considered "no-regrets," as the benefits associated with implementing such strategies are realized under current and future conditions regardless of future outcomes. In these instances, there is a strong economic case for immediate action.

2-1 PRIMER ON ECONOMIC METHODOLOGIES

This section reviews the conventional economic analyses used by transportation agencies for quantifying transportation investments and suggests ways these analyses may be used in a climate risk framework.[193]

Traditionally, economic analysis has been used to inform transportation decision making. For example, economic analysis might be used to demonstrate whether a potential transportation project makes economic sense to pursue considering the monetized costs and benefits over the serviceable life cycle of an asset. In considering costs, there are a number of metrics that can be quantified for transportation costs analysis at the

[192] Swiss Reinsurance Company (2011).
[193] Note that this discussion is not intended to discuss regulatory requirements for providing costs and benefits required for federal project funding.

agency-level, facility operations-level, and by transportation users (see Table 52). These metrics fall under the general categories of: construction, rehabilitation, and maintenance activities.

Table 52. Costs and benefits that can be quantified for transportation cost analysis (Source: adapted from USDOT (2003))

Agency Costs	• Design & engineering • Land acquisition • Construction • Reconstruction/rehabilitation • Preservation/Routine maintenance • Mitigation (e.g., noise barriers)
Users **Costs / benefits**	• Travel time (Facility operations) • Delay (Facility operations / Work zones) • Crashes (Facility operations / Work zones) • Vehicle operating costs (VOC) (Facility operations / Work zones)

In an economic analysis, agency costs represent the costs of the transportation project, while facility operation and user costs represent the benefits (this assumes that the project would reduce the impacts/costs to the facility operation and user). Transportation analysts measure the project costs and benefits by calculating the value of "C" as the sum of agency costs and social costs (e.g., traffic delays) and the value of "B" as the social benefits (as the sum of all avoided user costs).

Terminology and Metrics Useful for Economic Analysis

Inflation: measures the rise of prices for most goods and services. Best practices suggest: (1) not to account for inflation when forecasting life-cycle costs/benefits in an economic analysis (i.e., work with today's base year dollars); (2) include inflation in the project budget if the findings of (1) suggests economically viable project. There are simple formulas that can be used to adjust prices for inflation.

Is Inflation Removed from value?	Appropriate Dollar Terms to Use
Yes	• Real • Constant • Base year
No	• Nominal • Current • Data year

Discount Rate: is a rate that represents the time value of money. For example, money can be loaned or invested. If money is invested, there is an expectation of growth suggesting an amount of money today will be worth more in the future (perhaps growth of 5% per year). In the absence of inflation, if this money was loaned instead the money would not grow unless there was some agreed upon annual rate of return (e.g., 5%). When working with future dollars, a discount rate may be applied to estimate the present value. Because the choice of discount rate can have significant impact on estimating present value of costs and benefits, the discount rate should be a good representation of a State's actual time value of resources.

Simple Project Metrics

Net Present Value of Benefits (NPV): This metric takes the difference of the present value (PV), i.e., using a discount rate, of all costs and benefits of a project's lifecycle. If the benefits exceed the costs the NPV is positive and the project is worth pursuing.

$$NPV = Benefits - Costs$$

Benefit-Cost Ratio (BCR): This metric takes the ratio of the present value of the benefits to the present value of the initial agency investment cost. The ratio is usually expressed as a quotient (e.g., B \$2M/C \$1M = 2.0). This metric is used to select among projects when funding restrictions apply. For a given budget, the projects with the highest BCR can be selected, or used to form a package of projects that yields the greatest multiple of benefits and costs. If you are selecting more than one, normal practice is to group all the projects into bundles that are within the budget constraint, and see which collection gives you the greatest net benefit. Using B/C ratios doesn't get you there.

$$BCR = \frac{Benefits}{Costs}$$

Source: USDOT (2003).

The following economic analysis are useful for comparing transportation investments:

- Life-Cycle Cost Analysis (LCCA)
- Benefit-Cost Analysis (BCA)
- Economic Impact Analysis (EIA)

Each of the analysis is discussed in detail below. These analyses can generally be scaled to support varying levels of complexities, tailored to the specific project being analyzed.

2-1-1 Life-Cycle Cost Analysis (LCCA)

This method is an analysis, used in a wide range of governmental and industrial applications, that can be used to estimate the costs associated with the various choices (or "alternatives") to accomplish a given project or objective.[194] For example, an LCCA may be used when an agency has decided to move forward with a project and wants to compare the alternatives to identify the most cost-effective alternative. The LCCA sums the initial costs and future costs over the project's viable life; under conditions that the benefits are assumed to be equal among all projects. Essentially as a cost-only subset of Benefit-Cost Analysis discussed in the next section, LCCA identifies the most affordable means of accomplishing the proposed goal. For example, an LCCA may consider the life-cycle costs of building a tunnel.

Quantifying Direct Economic Impacts: LCCA

LCCA can help select across alternatives when benefits are essentially equal.

Uses in Climate Vulnerability/Risk Analysis

- Comparing adaptive strategies for a given asset

This analysis does not traditionally consider indirect costs.

Typical costs are summarized in Table 53, though only costs which will vary across the alternatives need to be included in the LCCA. The greatest variation of costs across alternatives tends to be user travel delay costs[195] and agency costs of construction and rehabilitation.[196] User crash costs tend to be omitted because of the substantial uncertainty in estimating these numbers; however, in a simple analysis, there may not be much variation across alternatives.

[194] USDOT (2003).

[195] The user costs vary across alternatives generally due to varying work zone requirements across alternatives. User vehicle operation costs in work zones may be small compared to travel delay costs. This cost can be estimated within a good degree of accuracy. USDOT (2003).

[196] USDOT (2003).

Table 53. Transportation costs that may be used in a LCCA (Source: adapted from FHWA (2003))

Agency Costs	• Design & engineering • Land acquisition • Construction • Reconstruction/rehabilitation • Preservation/Routine maintenance
Users Costs / benefits	• Delay (Work zones) • Crashes (Work zones) • Vehicle operating costs (VOC) (Work zones)

The LCC for a transportation project can be represented symbolically: [197]

$$LCC = \sum_{k=-(m-1)}^{n} C_k \frac{(1+j)^k}{(1+i)^k}$$

where m is the number of years in the development/acquisition phase, n is the operational lifetime, i is the discount rate, j is the inflation rate, and C_k is the cost incurred in the k^{th} year.

Life-Cycle Costs Analysis Steps

1. Establish design alternatives
2. Determine activity timing
3. Estimate costs (agency and user)
4. Computer life-cycle costs
5. Analyze the results

Source: US DOT (2002).

Applying this formula requires the following steps: (i) estimate of the useful life of the project; (ii) estimate of the yearly costs over the life-cycle; (iii) choice of a discount rate; and (iv) choice of an inflation rate.[198] The second step of estimating yearly costs over the life-cycle of the project can be the most challenging part of the LCCA. By including inflation in step iv, the yearly costs are estimated for nominal dollars. Office of Budget and Management's Circular A-94 provides standard and sensitivity cases for discount rates and future inflation that may be used in practice. [199]

Though LCCA can provide a useful estimate for comparing the costs of project alternatives, there are challenges,[200] the operational lifetime can be difficult to accurately forecast, particularly for projects considering new materials. The operational lifetime can also be problematic to estimate if future use could change substantially. For example, accurately projecting operational lifetime may be challenging for a project building a new coastal roadway that services a population whose neighborhood is projected to be underwater due to SLR between 2040 and 2060. To address this, it is general practice to adopt a standard value for operational lifetime. In addition, there can be substantial uncertainties in choosing an appropriate discount and inflation rate.

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[197] Eisenberger and Lorden (1977).
[198] Eisenberger and Lorden (1977).
[199] Office of Management and Budget (2015).
[200] Eisenberger and Lorden (1977).

2-1-2 Benefit-Cost Analysis (BCA)

Benefit-Cost Analysis (BCA) estimates both the life-cycle benefits and life-cycle costs of an individual project or objective. This is used to compare alternatives for a project when the benefits are not identical or across projects that may have different objectives. The goal of using a BCA is to identify the alternative that maximizes the net benefits to the public from the allocation of resources.[201]

> **Quantifying the Direct Economic Impacts: BCA**
>
> BCA can help select across alternatives when benefits are not equal.
>
> Uses in Climate Vulnerability/Risk Analysis
>
> - Comparing adaptive strategies across assets and locations
>
> This analysis does not traditionally consider indirect costs.

Transportation-related attributes that can be monetized include: "travel time costs, vehicle operating costs, safety costs, ongoing maintenance costs, and remaining capital value (capital expenditure and salvage value)."[202]

The benefits and costs typically considered in the alternatives are summarized in Table 55. When conducting a BCA, one of the alternatives developed is termed the *base case* and represents the "do minimal option", i.e., "the continued operations of the current facility under good management practices but without major investment." The other alternatives may be representative of adaptive measures. The major steps in a BCA are provided in the adjacent textbox.

> **Major Steps in the Benefit-Cost Analysis Process**
>
> 1. Establish objectives
> 2. Identify constraints and specify assumptions
> 3. Define base case and identify alternatives
> 4. Set analysis period
> 5. Define level of effort for screening alternatives
> 6. Analyze traffic effects
> 7. Estimate benefits and costs relative to base case
> 8. Evaluate risk
> 9. Compare net benefits and rank alternatives
> 10. Make recommendations
>
> Source: USDOT (2003).

There are a few considerations when conducting a BCA. (1) Many projects that use BCA or LCCA for investment evaluation do not consider the deterioration of the facility conditions over time, thus underestimating the user-costs. (2) As with the LCCA, the alternatives in a BCA may have varying operational lifetimes. To account for this, a multiyear analysis period is adopted for consistent comparison across alternatives. (3) When user benefits are large, it may be important to also consider forecasts of changes in traffic patterns to ensure an accurate assessment. The textbox entitled, "DOT Economic Analysis In Action", below describes the economic analysis of five recent DOT climate resilience pilots. The formulas and methodologies developed in these analyses are helpful building blocks to inform a "full" regional economic quantification analysis.

[201] USDOT (2003).

[202] Minnesota Department of Transportation (2016).

DOT Economic Analysis in Action

Over the past decade, the Department of Transportation (DOT) has conducted a number of climate resilience pilots across the United States. A few of these pilots considered economic impacts associated with potential adaptation projects (also termed "alternatives"):

- **The Minnesota DOT pilot**: This pilot used the COAST benefit-cost tool to evaluate the economic impacts of potential adaptation projects. COAST calculates the cumulative damages to transportation facilities over time using curves of water depths as a function of storm probabilities (e.g., 10-year storm) and curves of water depths as a function of damage costs (i.e., depth-damage functions). This study estimated the facility costs incurred from an event (e.g., flooding) over the lifetime of the facility as the "base case." The damage costs include physical damage costs, travel time delay costs, potential for motorist injury and fatalities. A discount rate of 2% was applied to translate future dollar estimates to present value costs. Then, for each adaptation option considered, the benefits (i.e., costs avoided) versus the incremental costs under possible future climate scenarios are calculated. The costs of each adaptation option was compared to the base case to identify cost savings. The benefit-cost ratio was then compared across the adaptation options to determine cost-effectiveness. The preferred adaptation options were ones with a benefit-cost ratio above 1 and were robust against the range of future climate scenarios.
- **The Oregon DOT pilot**: This pilot used a benefit-cost analysis (BCA) to compare a baseline approach to a "permanent fix" adaptive strategy. The benefits included time savings, reduction in vehicle operating costs, and increases in safety. The costs were either maintenance costs for the baseline approach, or the costs of the adaptive strategies.
- **The New York State DOT pilot**: This pilot used a BCA and considered both direct and indirect costs and benefits. Three categories of benefits were included social, economic, and environmental. Social benefits included safety, mobility, and accessibility to critical services, such as hospitals; economic benefits included avoided flood repair costs, avoided costs to repair environmental degradation, and avoided freight disruption; and environmental benefits included healthier fish and wildlife, improved river habitat, less erosion, improved water quality, and increased river recreation. Social and economic benefits were calculated in dollar values. Environmental benefits were included by using a multiplier.
- **The DOT Gulf Coast Phase 2 study**: This study used a Monte Carlo analysis for conducting the BCA. The Monte Carlo process is used when the exact input values are unknown. The analysis considers the possible variation across a range of inputs to create many outcomes. Then those outcomes are processed and analyzed to create a probability distribution of outcomes.
- **The DOT Hillsborough pilot**: This pilot used the Regional & Economic Models, Inc. (REMI) tool to calculate the economic losses associated with the disruption of specific vulnerable transportation facilities and the cost-effectiveness of adaptation strategies. REMI was driven with inputs of hours of travel time delay, vehicle miles traveled, and lost commuter and truck trips to provide changes in Gross Regional Product (GRP), income, and labor hours over a five-day (business week) period.

Source: MnDOT (2014); Oregon Department of Transportation (2014); NYSDOT (2016); USDOT (2014); Hillsborough County MPO (2014).

For additional information regarding FHWA pilots, see: http://www.fhwa.dot.gov/environment/climate_change/adaptation/resilience_pilots/index.cfm

Recognized Limitations with NPV, LCCA, BCA

There are limitations of the conventional BCA, Net Present Value (NPV) and LCCA methods for determining transportation network costs and benefits, including the open-ended range of agency-costs and user costs that can potentially inflate either the full project costs or its benefits, depending on how they are manipulated. To avoid these pitfalls, the USDOT FHWA has recommended that two improvements be made to the process of cost analysis:

1) Only the initial agency investment cost be included in the denominator of the ratio; with all other BCA values (including periodic rehabilitation costs or user costs such as delays associated with construction) to be included in the numerator as potential positive or negative benefits; and
2) To avoid overestimating the benefits of a project, care should be taken not to include as "benefits" what is simply a restatement of what has been calculated as part of an economic impact study as benefits of job and business growth (and added to safety and travel time savings) to avoid potential long-term double-counting of the benefits.[1]

Source: USDOT (2003).

[1] The Texas Transportation Institute (TTI) has developed the MicroBENCOST model to implement the AASHTO guidelines for measuring user benefits from highway projects.

2-1-3 Economic Impact Analysis (EIA)

Given some of the limitations of conventional BCA and LLCA methods of calculating project costs and impacts, an economic impact analysis (EIA) may be preferred as this analysis incorporates broader indirect measures of economic and climate-change impacts on the transportation infrastructure performance and costs. For example, an EIA may include monetary effects on employment patterns, wage levels, business activity, tourism, and housing.[203] In other words, an agency might first conduct a BCA to monetize the direct economic impacts of a project, and then use these results to inform the EIA which monetizes the related indirect economic impacts (e.g., jobs, land-use, etc.). An EIA is a "complimentary analysis to the BCA."[204] EIA integrates travel demand models, land-use, and dynamic input-output economic interaction. It is important to note that the monetary value of the indirect effects in an EIA is not additive to the value of BCA-measured direct effects. Faster commuting time,

Quantifying the Indirect Economic Impacts: EIA

EIA can enhance a BCA by considering the costs associated with the indirect economic impacts across alternatives.

Uses in Climate Vulnerability/Risk Analysis

- Comparing adaptive strategies across assets and locations

This analysis traditionally can include direct and indirect costs/benefits.

[203] USDOT (2003).
[204] USDOT (2003).

for instance, may induce more people to move further away from work place; this new demand for more remote properties drives up the price of remote property. Thus the highway user translates part of the value of his travel time savings to the owners of suburban properties. An EIA is conducted when a project is justified not solely on the benefits generated at the project level, but when broader benefits can accrue, or damages are averted.[205] An EIA is also useful for providing additional information when there are competing interests supporting various alternatives of a project.

There are a number of EIA methodologies, including:[206]

- Survey studies: This is a qualitative approach drawing on expert interviews, vehicle origin-destination logs, corridor information, etc.
- Market studies: This "consider[s] demand and supply for business activity to quantify market of a change in transportation costs caused by a project."
- Comparable case studies: This "evaluate[s] the localized economic impacts of a project on neighborhoods, downtowns, or small towns [(e.g., bypassing a small town)]."
- Sophisticated econometric analysis and economic modeling, including productivity impact analysis (considering productivity benefits not generally included in a BCA) and regional economic models.

As the need for greater precision and analytical breadth of BCA tools grows, more sophisticated EIA studies are done with Input-Output models that capture aggregate regional economic effects.

Input-Output (I-O) models are a type of regional economic modeling and are readily available economic analysis tools that enable consideration of broad range of direct and indirect economic impacts resulting from an infrastructure disruption. I-O models are static, in that they provide a "snapshot" of economic effects in reaction to a disruption (i.e., they do not provide the potential cumulative economic effects over time). This suggests these models are particularly useful for considering the short-run impact of a given extreme event or under a future scenario where adaptation strategies were implemented and the extreme event occurred under future conditions (e.g., sea level rise). Input-Output models such as Regional Input-Output Modeling Systems, 2nd edition (RIMS II) and Impact M for Planning (IMPLAN) are among commonly deployed tools for estimating the full impacts of changes in the transportation network on the regional economy. The advantage of I-O models is that they can be applied to any geographic level where Bureau of Economic Analysis (BEA) data are available. Refinements of I-O models can focus on specific segments of the transportation network, ports, rail facilities, power stations, etc., at the regional or sub-metropolitan level.[207]

Data sources for I-O models include BEA data on flows of production inputs (raw materials, labor, etc.) and output (services and manufactured products) in the region. BEA provides measures of the annual national

[205] USDOT (2003).
[206] USDOT (2003).
[207] BEA data sources include National Income Accounts, Satellite Accounts, I-O Accounts, and Tradestats Express database containing data on imports and exports at the national level and exports at the state level.

output by NAICS (North American Industry Classification System) industry class. Using these data, I-O models such as RIMS II, IMPLAN, and Regional Economic Model, Inc. (REMI) provide output- and demand-driven multipliers to indicate the extent to which each dollar of direct spending circulates in the economy to generate additional income benefits in the region. These I-O models and CGEs are described below.

Economic impact metrics commonly quantified by the tools described in this section

- **Direct economic impact***,* measured by multiplying the region's GDP per worker/per day by industry sector (transport sector in general or specific subsectors ports, etc.) output times the number of lost worker days. Summing this across all affected sectors yields the total direct GDP costs;
- **Indirect economic impact***,* measured as indirect loss in other related sectors and households through losses of input materials purchased, lost incomes (which affects spending across all industries);
- **Induced impacts** are the losses from reduced activities of other sectors resulting from the damages to the facilities of the primary sectors directly impacts;
- **Total impacts** are estimated by multiplying the direct impacts by the RIMS II multipliers. These multipliers translate a dollar of direct economic impact in a region/industry into a total economic impact. These multipliers simulate the successive rounds of expenditures taken place through the economy as a result of a change in expenditures in an industry/region. The estimated indirect impacts are then determined by subtracting the direct impacts from the total impacts.

Regional Input-Output Modeling System (RIMS II)

RIMS II, developed and maintained by the Department of Commerce, is a fee-based data service by the U.S. Bureau of Economic Analysis (BEA). BEA is the primary agency of the federal government that compiles economic information. BEA also produces the Benchmark Input-Output (I-O) accounts of the U.S. Economy, which are used for building I-O models. [208] RIMS II provides a regionally- or state-specific set of total final demand multipliers for total industrial output; value added; earnings (labor income); and jobs (so that users can use them rather than generating their own multipliers).[209] The model is based on an I-O table that shows the industrial distribution of inputs purchased and inputs sold for any of up to 369 detailed industry sectors. The inputs include not only the costs of raw materials for production, but also labor (household sector). Data from RIMS II show the multipliers for each dollar spent on inputs and outputs to represent the extent to which every dollar of change in an industry's input and output affects all other industries. As such, the multipliers quantify the way a dollar injected into one sector is spent and re-spent in other sectors, generating subsequent activity that affects the entire regional economy. RIMS II's advantage is that it uses readily

[208] See: http://www.bea.doc.gov/rims.

[209] (Note: Availability of RIMS II through the BEA has been discontinued because of sequestration and reduction in FY 2013 funding levels. Unless funding is restored at some future date, RIMS II will not be available.)

available BEA data sources, is a simple to use spreadsheet-based tool, and is relatively inexpensive, costing between $2K and $5K.

Impact Analysis for Planning (IMPLAN)

The Minnesota IMPLAN Group's Impact Analysis for Planning (IMPLAN) is a computer-based economic impact analysis model that uses data sources readily available from BEA, with the capability for modification of the regional or national variables. IMPLAN calculates the impacts of a change in its inputs and outputs, displaying them as traditional direct, indirect, and induced effects.[210] Through its Social Accounting Matrix (SAM) modeling, the I-O table accounts for all dollar flows between different sectors of the economy; using this information, IMPLAN models the impact of the economic multiplier throughout the region. A key capability of IMPLAN is the spatial definition of the area of analysis, which in IMPLAN can range from state to county to zip code. Unlike other static I-O models that just measure the purchasing relationships between industry and household sectors, SAM also measures the economic relationships between government, industry, and household sectors, allowing IMPLAN to model transfer payments such as unemployment insurance. IMPLAN is a more expensive I-O tool ($5K-$15K) than RIMS II but has the advantage of allowing a dynamic application of the multipliers to the impacted industries.

Regional Economic Models, Inc. (REMI)

Regional Economic Models, Inc., or REMI is a comprehensive economic accounting model that relies on the BEA data on employment wages, and personal incomes to estimate the impacts of a change in demand or supply of inputs through five sets of metrics: 1) output; 2) labor and capital demand; 3) population and labor supply; 4) wages/prices/profits; and 5) market shares. Relative to other economic modeling tools, REMI is expensive, costing between $2k and $100k.[211]

Computable General Equilibrium (CGE) Models

CGE models have been introduced in recent years to supplement I-O models for impact analysis, providing the capability to predict the behavior of businesses and individuals when faced with a disaster. CGE is a "multi-market simulation model based on simultaneous equations optimizing behavior of individual consumers and firms, subject to economic accounts balances, and resource constraints." CGE models provide a valuable framework for analyzing natural hazard impacts and policy responses, and measuring the effectiveness of adaptation responses. These models incorporate micro-, meso-, and macro-level effects through the business production response to aggregate categories of major inputs of capital, labor, energy, materials, and transportation subgroups.[212]

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[210] Induced impacts in some models have been interpreted as the "catalytic effects" models that estimate the "net economic effects (employment, income, government revenues) resulting from the contribution of expansions in a transportation system such as air transportation on tourism and trade, and its long-term effects on GDP and productivity. These effects may be construed as "spillover" effects that are not measured through their direct or indirect impacts.

[211] Citizens Climate Lobby (2014).

[212] Rose and Lia (2005).

At the regional level, data can be obtained on two key components of loss from a disaster: a) flow measures: e.g., output, income, and employment losses, which are just as important as b) stock measures of loss to property and infrastructure assets. The stock and flow measures can take into account the full range of economic assets and actual and potential losses (including loss of use and loss of consumer surplus) for the region. CGE models can also incorporate capital-asset losses (discounted flows) of present and future value of flow disruptions, as well as un-priced non-market values and externalized losses. Such capabilities make CGE models able to potentially mimic the role of markets and prices. To this extent, CGE models are dynamic and might be able to account for an entirely new path of economic growth. In other words, the IO models tend to me more rigid but valuable for a short run analysis, while the CGE models may provide more information about responses over time, as market adapt to new conditions.

2-2 RESOURCES FOR ASSESSING TRANSPORTATION ASSET VULNERABILITY AND QUANTIFYING ECONOMIC IMPACTS OF CLIMATE CHANGE

> *Approaches to climate change are shifting from a disaster-response-focused approach to a risk-management approach that seeks to build resistance to climate-induced impacts through making systems more robust and resilient.*
>
> Source: Field et al. (2012).

Several useful tools have been developed in the past decade that can be adapted to consider and/or quantify the impacts of extreme weather and/or climate change on the transportation system and the associated economic consequences. Prior to an economic analysis, there needs to be an understanding of which transportation assets or systems are vulnerable to a changing climate or extreme weather event and potential adaptive measures that may enhance resilience. To date, transportation climate assessment studies follow a variety of methods dependent on purpose and expertise. However, underlying these choices tend to be the fundamental steps as illustrated in the Department of Transportation (DOT) Adaptation Framework (see Figure 1). Some of the resources available for assessing vulnerabilities and considering adaptive strategies include the following tools developed by USDOT and NCHRP:

- Vulnerability Assessment Scoring Tool (VAST): Provides a framework to evaluate potential climate-related vulnerabilities across transportation assets. In addition, VAST provides a library of generic sensitivity and adaptive capacity indicators across transportation asset type and climate stressor. VAST could be enhanced by using economic drivers as additional criteria in identifying critical assets and associated sensitivities and adaptive capacity.

- Costing Asset Protection for Transportation Agencies (CAPTA): Provides a framework that could be tweaked to identify adaptive strategies that may make economic sense in addressing the impacts of climate change.

Once the vulnerable assets of greatest concern are identified along with a collection of potentially economically viable adaptive strategies, an economic quantification at either the asset or programmatic level can be conducted. Figure 40 provides a qualitative illustrative example of one way these tools could connect.

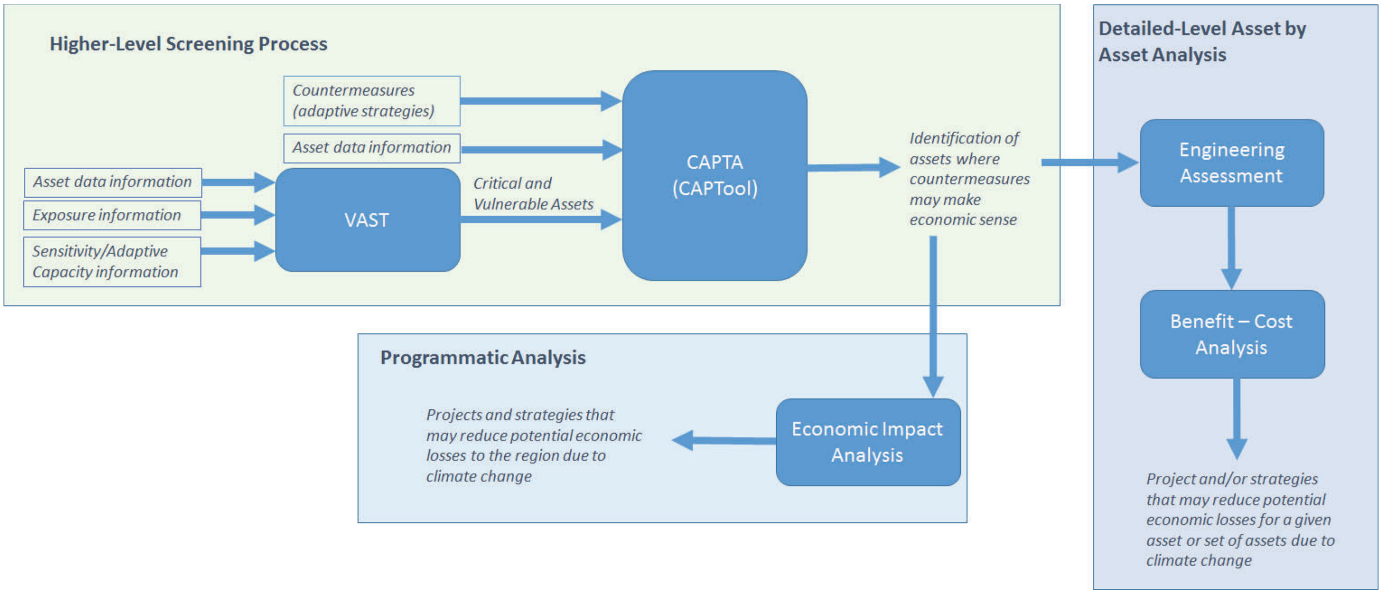


Figure 40. Schematic of pathway the tools discussed in this section may inform economic analysis at program or asset level (Source: based on discussion provided in this section)

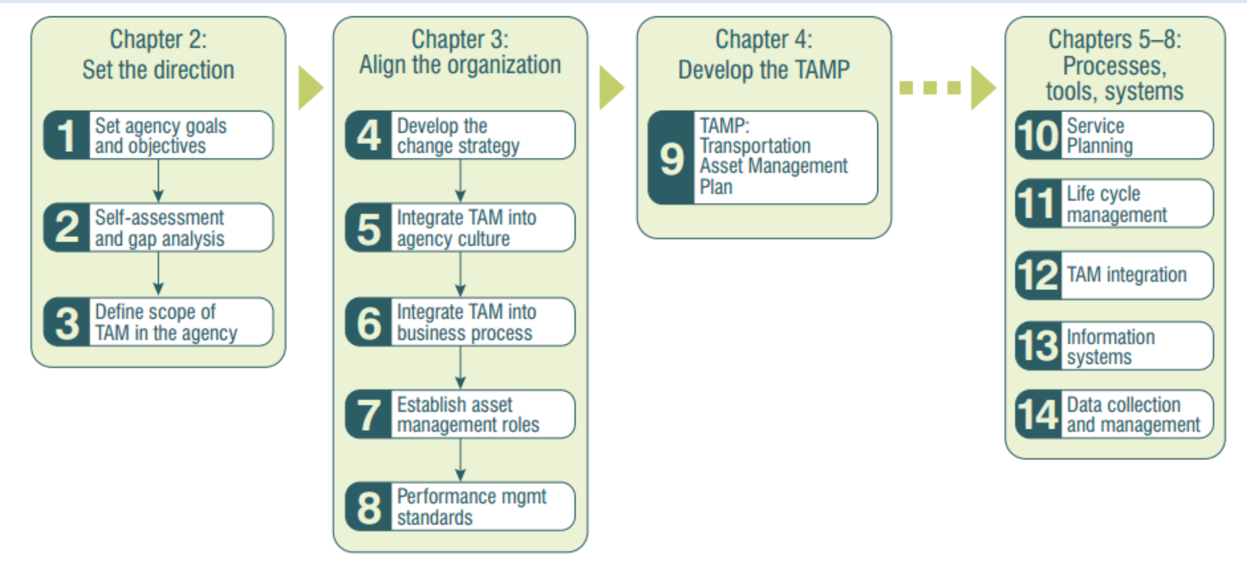
Resources for Asset Management and Planning

Preparing for Natural Disasters. In compliance with the Presidential Policy Directive 8 (PPD-8) requirements for nation preparedness, FEMA worked with interagency partners to develop the National Disaster Recovery Framework (NDRF). The framework is a report that guides disaster-affected states, tribes, or local-communities through effective pre- and post-recovery, including the transportation infrastructure.

Transportation Asset Management. For decades, state DOTs have been conducting transportation asset management (TAM) as part of the decision process for investment in maintenance and capacity enhancement projects. With implementation of the Moving Ahead for Progress for the 21st Century Act (MAP 21), TAM moved closer to incorporating climate-related risks into its asset management decision process.

In 2012 and 2013, FHWA used TAM as a platform for evaluating and addressing extreme weather impacts by releasing a series of reports on risk-based asset management. TAM's applications for managing risks can be broken down into 14 main steps, with each step setting the direction for aligning the agency's project investments with the organization's asset-management responsibilities (see Figure below). TAM's final five steps articulate the extreme weather risk-management steps—service planning, life-cycle management, and the steps leading to integration of climate-related information systems and data-collection functions into TAM. These functions have been consolidated into the TAM Information System or (TAMIS), a tool that integrates the agency tasks relating to climate change risk into the state TAM functions. The TAMIS tool incorporates four datasets—asset inventory, inspection, condition, and work history—each of which is a key source of information on extreme weather events, asset vulnerabilities, and potential adaptation measures.

TAMI Implementation Steps



Source: American Association of State Highway and Transportation Officials (AASHTO) (2011).

2-2-1 The VAST Tool

The Vulnerability Assessment Scoring Tool (VAST) was developed by USDOT for use by planners and asset-managers to assess how assets in their transportation system may be vulnerable to climate stressors. This spreadsheet-based tool does not consider event-related or adaptive costs and benefits; it is a tool for identifying which assets may be most vulnerable when populated with user information. VAST uses indicators to develop quantitative vulnerability scores for five categories of assets: roads, ports, airports, rail, and transit. The USDOT Gulf Coast Phase 2 Study developed VAST as an asset-specific vulnerability model that identifies characteristics that serve as indicators of their exposure, sensitivity, and adaptive capacity.[213] A Vulnerability Score for each critical asset is based on the vulnerability formula:[214]

Vulnerability = f (Exposure, Sensitivity, Adaptive Capacity)

VAST identifies exposure levels, asset sensitivity, and capacity to adapt; and produces a scoring dashboard to reflect the scale of threats and mitigation measures (see Figure 41).[215] The example dashboard shows a summary of the vulnerability of roads to temperature change, precipitation change, and storm surge. Each climate stressor is considered with two scenarios representing a small amount of future change (e.g., "low scenario") and a larger amount of future change (e.g., "high scenario"). This is a technique that many within the climate planning community use to bound the future plausible futures based on the state of the science. To arrive at these results, the user has already tailored VAST with exposure indicators (e.g., temperature change may use "maximum high temperatures sustained over three days" as an indicator), sensitivity indicators (e.g., 3-day temperatures above a given threshold(s)), and adaptive capacity. In this example, storm surge only affects a portion of the study area, in which case some roads entered in VAST are simply not exposed to storm surge. The vulnerability scoring is from 0 to 4, with 4 representing the most vulnerable.

Asset Types

- Rail lines
- Ports
- Airports
- Transit assets
- Buildings
- Boardwalks
- Bridges
- Culverts
- Docks
- Parking lots
- Pavement
- Pavement inlets
- Piers
- Pipes
- Retaining wall
- Signs
- Storm sewer pipes
- Trains
- Traffic signals
- Tunnels
- Other (User-defined)

Climate Stressors

- Temperature Change
- Precipitation Change
- Sea Level Rise
- Storm Surge
- Other (User-defined)

[213] USDOT Gulf Coast Phase 2 Study website: https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/.
[214] FHWA; Mike Savonis, ICF International.
[215] USDOT (2015).

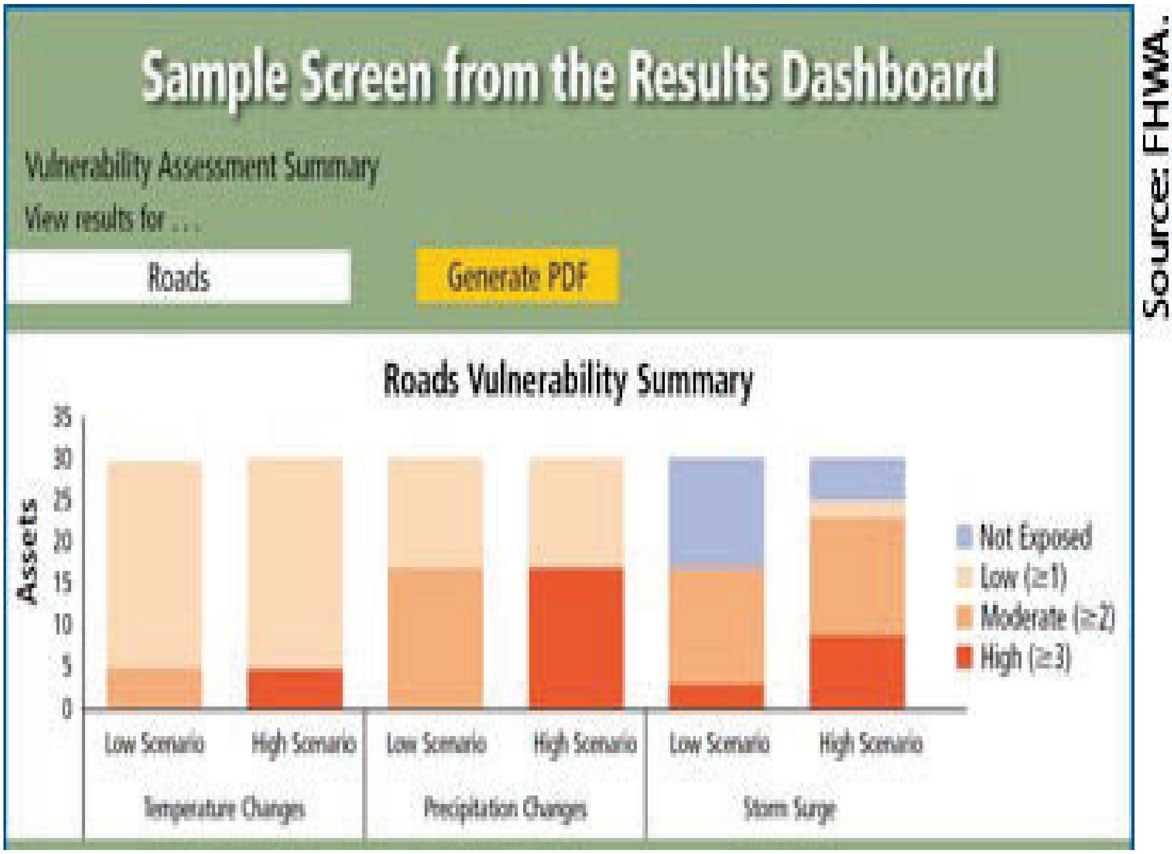


Figure 41. VAST dashboard. (Source: USDOT)

VAST requires the user to populate the tool with quite a bit of information; however, this allows for a flexible and tailored analysis. First, the tool requires that asset managers collect a range of asset data (see Table 54).[216] The exposure information can be collected or processed through various sources as described in the user's manual, including DOT's Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool which processes a number of climate models to obtain a set of future changes for temperature and precipitation variables.[217]

[216] USDOT (2015).

[217] The World Climate Research Programme's (WCRP) fifth phase of the Coupled Model Inter-comparison Project (CMIP5) provides a standardized experimental protocol for studying the output of climate models developed by 20 modeling groups. For the United States, many of these large-scale climate model output of daily temperature and precipitation have been downscaled to fine-scale climate model output using a statistical technique based on gridded observations. DOT FHWA provides a tool, the CMIP Climate Data Processing Tool, for post-processing this fine-scale climate data to provide transportation-relevant climate stressors (e.g., number of days per year above 95^{o}F). This tool is part of CMIP Data Processing Tools available at FHWA's climate adaptation website.

Table 54. Types of data to be collected for VAST (Source: VAST User's Guide)

ASSET DATA	ADDITIONAL DATA
▪ AGE OF ASSET ▪ GEOGRAPHIC LOCATION ▪ ELEVATION ▪ CURRENT/HISTORICAL PERFORMANCE AND CONDITION ▪ LEVEL OF USE (TRAFFIC COUNTS, FORECASTED DEMAND) ▪ REPLACEMENT COST ▪ REPAIR/MAINTENANCE SCHEDULE AND COSTS ▪ STRUCTURAL DESIGN ▪ MATERIALS USED ▪ DESIGN LIFETIME AND STAGE OF LIFE	▪ LIDAR (LIGHT DETECTION AND RANGING) REMOTE SENSING DATA ▪ FEDERAL EMERGENCY MANAGEMENT (FEMA) MAPS ▪ VEGETATION SURVEY

VAST suggests a number of exposure indicators for precipitation and temperature (see Table 55). The temperature exposure indicators can be processed using climate model outputs, such as through the DOT CMIP Climate Data Processing Tool. There are a number of sources that can be used to inform the precipitation exposure indicators, such as: DOT CMIP Climate Data Processing Tool, FEMA Digital Flood Insurance Maps (DFIRMs), flood insurance studies, feedback from maintenance and emergency management staff, and local universities. The scoring of these indicators is from 1 to 4 with 1 suggesting no significant change in exposure and 4 suggesting significant exposure.

Table 55. List of exposure indicators provided in the exposure indicator library in VAST (Source: VAST tool)

TEMPERATURE EXPOSURE INDICATORS	PRECIPITATION EXPOSURE INDICATORS
▪ Change in total number of days per year above/below a threshold temperature ▪ Change in longest number of consecutive days per year above/below a threshold temperature ▪ Change in number of freeze-thaw cycles per year ▪ Change in annual maximum and minimum temperature ▪ Change in annual mean temperature	▪ Change in amount of rain associated with 100-year 24-hour storm ▪ Location in FEMA 100-year flood zone ▪ Location in FEMA 500-year flood zone ▪ Location in 10-year Floodplain ▪ Location in 25-year Floodplain ▪ Change in Number of Consecutive Days with Precipitation ▪ Change in Total Seasonal Precipitation ▪ Change in Total Annual Precipitation ▪ Change in Peak Discharge ▪ Change in Flow Velocity ▪ Change in Discharge Volume

VAST suggests a number of sensitivity indicators by asset class and climate stressor (see Appendix D for a full table of sensitivities as provided by the VAST Tool library). For example, a sensitivity indicator for bridges might be truck traffic. For each sensitivity indicator included, the user must determine what ranges of values represent the 1 ("low sensitivity") to 4 ("high sensitivity") scores. VAST suggests a number of sources to assist

in data development, such as: interviews/survey/conversations with operations and maintenance staff, maintenance or repair records, emergency response records, National Bridge Inventory, engineers, and owners and operators.

VAST further provides a library of adaptive capacity indicators that can be useful to collect. For example, an indicator of port adaptive capacity to an extreme weather event might be the redundancy within a facility. A cross-walk between these indicators and asset management information can be useful to identify most vulnerable assets.

2-2-2 CAPTA: A Consequence-Based Risk Management Tool

The National Cooperative Highway Research Program (NCHRP) report, "Costing Asset Protection: An All Hazards Guide for Transportation Agencies," (CAPTA) is a guide for transportation practitioners to evaluate the consequences of threats/hazards on critical multimodal transportation infrastructure assets. Part of this work included the development of the Costing Asset Protection Tool (CAPTool). The CAPTool is an asset management tool in the form of an Excel spreadsheet that provides a set of guidelines for identification of critical or high-cost assets and evaluation of the potential countermeasures (i.e., mechanisms for reducing harm).[218] The CAPTA methodology uses a standard risk model $R = f(T, V, C)$ for quantifying threats ("T"), vulnerabilities ("V"), and consequences ("C") to measure the community's relative susceptibility to the consequences of hazards. However, CAPTA is not intended as a formal risk model as it does not require the user to estimate the likelihood of the event but, instead, the user identifies the hazards of concern.[219]

CAPTA is a multi-step process starting with asset identification with the CAPTool automating a significant portion of the CAPTA methodology (see Table 56).[220] The CAPTool considers 8 asset classes - including road bridges, road tunnel, transit/rail bridges, transit/rail tunnels, transit/rail stations, administration and support facilities, ferry, and fleets. The user can select which asset classes are appropriate for the analysis and will then need to identify the critical assets that they want to consider in the analysis. The hazards/threats considered include:

- Natural events (flood, earthquake, extreme weather, mud/landslide);
- Unintentional events (fire, power loss, equipment breakdown, structural failure, hazardous material);
- Intentional threats (small explosive devices, large explosive devices, chemical/ biological / radiological agents, criminal acts).

Of these hazards/threats, the flood and extreme weather within the natural event category are directly applicable to the HR analysis of costs associated with climate-related events and adaptive measures. The CAPTool does not simulate what assets may be exposed during a flood event, but considers if a flood event

[218] NCHRP (2009).
[219] Though natural events have historical data that can be used to assess likelihood of the event, it is not included to maintain consistency across all threat categories.
[220] FHWA (2013a).

were to occur, which assets exceed the consequence thresholds (as described below) to warrant further consideration of countermeasure investments.

Table 56. CAPTA methodology with steps in yellow performed within CAPTool (Source: FHWA (2013a))

A.	Identify Assets
B.	Collect Data
1.	Identify Threat/Hazard Asset Classes (Relevant Risk Tab)
2.	Establish Consequence Thresholds (Thresholds Tab)
3.	Describe Infrastructure Assets (Multiple Assets Tabs)
4.	Identify Critical Assets Across Modes (Critical Assets Tab)
5.	Identify Countermeasure Opportunities (CM Opportunities Tab)
6.	Generate Summary Report (Results Summary Tab)
7.	Re-run CAPTool with Updated Assumptions, Budget Realities, or New Assets

A key component of CAPTool is the user-defined "Consequence Thresholds" for each asset-class considered. The Consequence Threshold is the point at which the impact of the threat/hazard is significant enough to warrant consideration of countermeasure investments. These thresholds include: potentially exposed population,[221] property loss,[222] and mission importance[223] (e.g., demand percentile for ADT*Detour Length for a road bridge asset class). In determining applicable hazard/threat thresholds, the user may also consider such information as the National Fire Protection Association, FEMA's National Flood Protection Act (NFPA) guidelines, or other engineering standards.

Table 57 outlines the components of the CAPTA consequence thresholds composed of three key decision factors: potentially exposed population (PEP), potential value of assets at risk of loss, and the mission-critical equation for bridge assets. CAPTool applies a series of equations to determine whether an asset is above the user-specified threshold consequence levels.

[221]Potentially exposed population refers to the population that could be harmed by the maximum threat/hazard. This consequence tends to be well-correlated with delays to emergency response, etc.
[222] Property loss is the cost to replace an asset type (units of millions of dollars).
[223] Mission importance describes the relative importance of the assets and the volume of use, including loss of function and/or transport delays. An exception is road bridges which considers the product of ADT and detour distance.

Table 57. Threshold consequence determination (Source: NCHRP (2009))

ASSET	POTENTIALLY EXPOSED POPULATION EQUATION	PROPERTY EQUATION	MISSION EQUATION
ROAD BRIDGES	Separated into primary direction and secondary direction – for each, if vehicles/lane >2400 assume 40 vehicles/1000 feet. Otherwise, if lower assume 7.5 vehicle/1000 feet.	$20,000/lane feet	(ADT) x (detour length) 75th, 85th, 95th percentile as thresholds relative to typical bridge inventory (Example is based on the National Bridge Inventory)
ROAD TUNNELS	See above	$100,000/lane feet	User input for criticality
TRANSIT/RAIL STATION	4 x (maximum capacity of rail cars)	Below ground = critical	User input if transfer station is critical
TRANSIT/RAIL BRIDGE	2 x (maximum capacity or rail cars)	$15,600/lane feet	User input is percentage of ridership that regularly use this transit/rail transportation asset
TRANSIT/RAIL TUNNEL	2 x (maximum capacity of rail cars)	$40,000/feet	User input is percentage of ridership that regularly use this transit/rail transportation asset
SUPPORT FACILITIES	1 person/175 square feet	$210/square feet	Never critical unless so designated by user
FERRIES	Maximum capacity of ferry	User input	Never critical unless so designated by user
FLEET VEHICLES	Maximum occupancy of one fleet vehicle	Average cost per vehicle x maximum number of vehicles	Never critical unless so designated by user

The CAPTool has varying data requirements depending on which asset classes are considered (see Figure 42). The user inputs each specific asset within the asset class that are critical and provides the corresponding data.

	Category							
Required Data	Road Bridges	Road Tunnels	Transit/Rail Stations	Transit/Rail Bridges	Transit/Rail Tunnels	Admin & Support Facilities	Ferries	Fleets
Identification of asset or asset class	•	•	•	•	•	•	•	•
Quantity	•	•	•	•	•	•	•	•
Annual average daily traffic	•	•						
Length (ft.)	•	•		•	•			
Travel lanes	•	•						
Detour length to nearest available crossing	•	•						
Type of construction	•			•				
Replacement cost	•	•	•	•	•	•	•	•
Maximum train capacity (occupancy)			•	•	•			
Knowledge that structure is below grade/above grade			•					
Knowledge that station is a transfer point			•					
Percentage of total ridership using the tunnel (or bridge)				•	•			
Square footage of facility						•		
Maximum occupancy of facility						•		
Maximum occupancy (persons)							•	
Maximum occupancy (vehicles)							•	•
Average cost per vehicle								•

Figure 42. List of required data for use in CAPTool (Source: FHWA (2013a))

CAPTool then provides a series of worksheet results, including: (1) which asset(s) exceed which consequence threshold for a given hazard/threat; (2) the effectiveness of countermeasures for each asset; (3) a summary page detailing the consequence thresholds, number of critical assets, and costs of countermeasures aggregated to the asset class level. CAPTool considers a range of potential countermeasure categories, including: prediction/intelligence gathering, detection, interdiction, response/preparedness, design/engineering measures. A full list of countermeasures are provided in Appendix C. Countermeasure costs are determined by using logical cost assumptions from the RSMeans cost estimating manual.[224] The user may also define additional countermeasures.

[224] The RSMeans cost manual is available at: http://www.rsmeans.com.

2-2-3 Multi-Criteria Decision-Making

FHWA partnered with Virginia DOT (VDOT) to conduct the 2010-2011 Hampton Roads Pilot for climate change vulnerability assessment in collaboration with the University of Virginia.[225] A key component of the VDOT Hampton Roads pilot study is the Multi-Criteria Decision Analysis (MCDA) model. The MCDA model helps prioritize investments for long-range transportation planning by using multiple future scenarios considering future changes in climate, economic projections, new technology, change in land use, etc. The tool requires minimal modeling or computational resources. Because it is automated and scales easily, MCDA allows for study of large networks. If these networks/structures were studied on an individual basis—rather than multi-criteria impact evaluation—they would likely result in either oversimplifying the impacts, or overlooking certain factors. MCDA is designed to handle multiple conflicting objectives and assess vulnerability for future uncertain conditions.[226] Figure 43 illustrates the structure of the MCDA developed for Virginia and tested in the HR pilot.

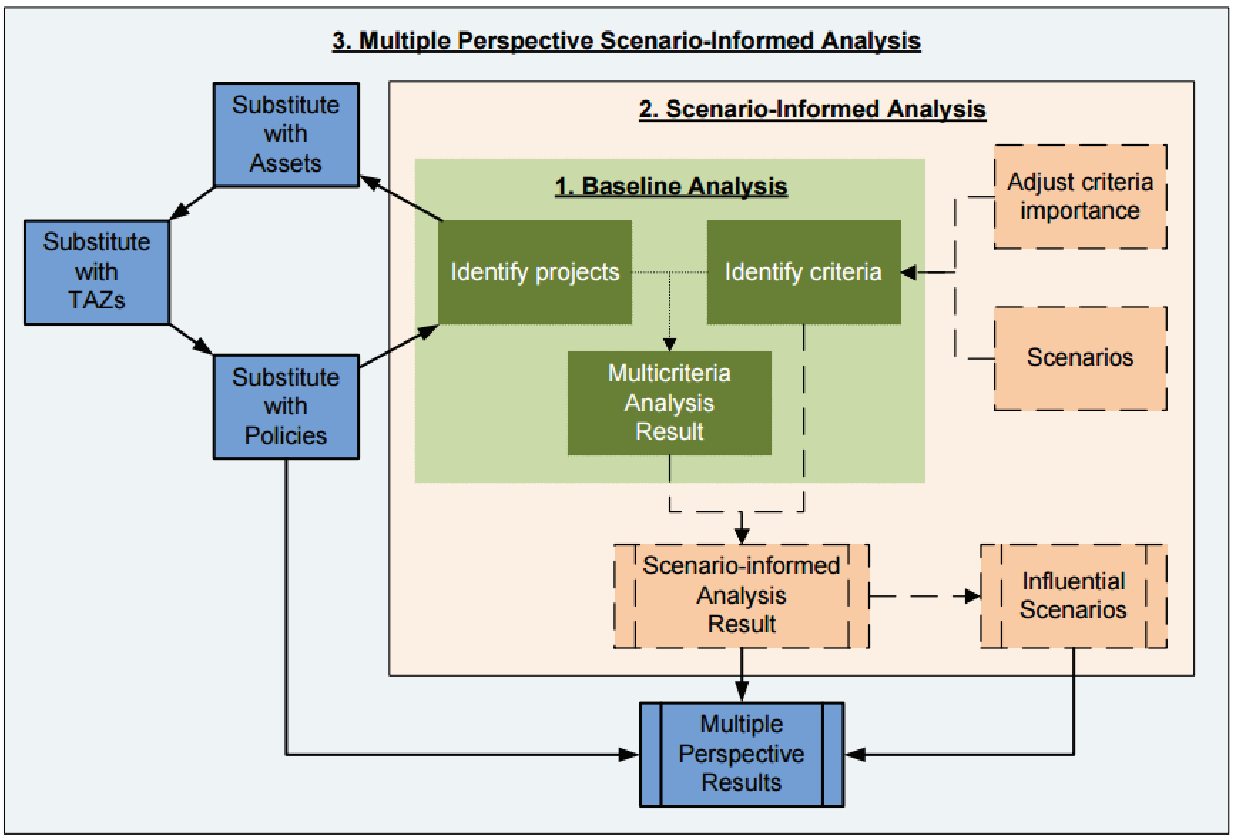


Figure 43. Structure of the Virginia model supporting the FHWA framework (Source: VDOT et al. (2012))

The Pilot methodology was driven by the priorities and infrastructure projects underway within the region. Climate change scenarios were combined with projections of economic condition, GDP growth, and maintenance/funding policies. All of these led to development of scenarios and models that were run to

[225] VDOT et al. (2012); FHWA (2011b).

[226] For research on MCDA, see: Kirshen et al. (2011).

measure the climate impacts and create new priorities for existing transportation assets, major transportation projects, transportation analysis zones (TAZs), and multimodal polices.

One tool, the MCDA, simulates how changes in transportation stressors, like climate change and the economy, may affect the prioritization of projects. Specifically, the MCDA Excel-based worksheet considers which of the HR Long-Range Transportation Projects Prioritization Criteria are affected by changes in climate (e.g., increase in SLR, increase in extreme heat days) and changes in non-climate conditions (e.g., economic recession, energy shortage). For a case study, the MCDA evaluated 155 transportation projects planned over the next thirty years. The user chooses up to five scenarios in which the user "turns on" various climate and non-climate conditions (e.g., increase in sea level rise, changes in land use regulations). The user then revisits the Prioritization Criteria and, through expert knowledge, considers how each scenario may impact the Prioritization Criteria choosing from major decrease, minor decrease, minor increase, and major increase. MCDA Tool then calculates the change in the total score for each project under each scenario.

Figure 44 shows the matrix of the scores across projects (columns). For each project, the score is provided under baseline conditions (no changes in climate and non-climate conditions) compared to changes in scores for the 5 user-defined scenarios. This provides insight as to how each scenario may influence the scoring of a given project.

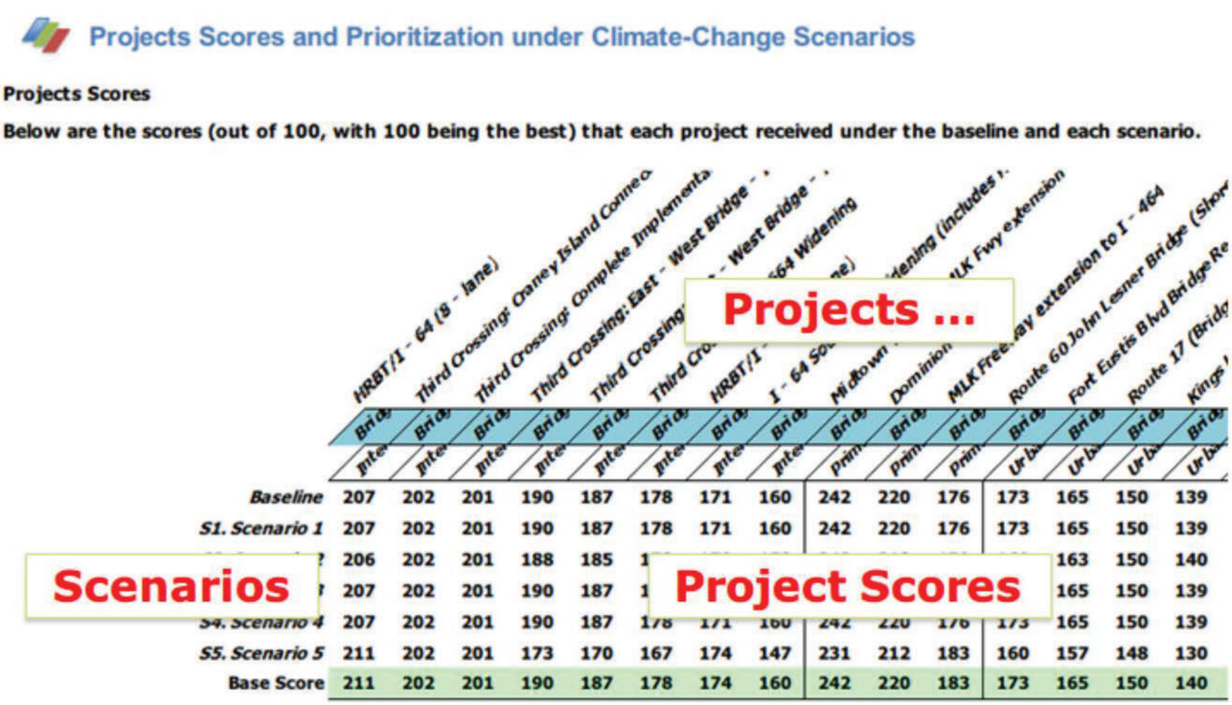


Figure 44. Matrix of the Scores for each of the climate scenarios in the FHWA MCDA assessment for Hampton Roads (Source: VDOT et al. (2012))

2-2-4 Haimes' Inoperability Input-Output/Multi-Criteria Risk-Filtering Model

This section discusses the Input-Output risk assessment and risk prioritization/filtering tool, developed by Professor Yacov Haimes and his colleagues at the University of Virginia, Center for Risk Management of Engineering Systems (CRMES) for management of climate change risks in HR and elsewhere.[227] His multi-component model serves as an overarching conceptual framework for risk assessment. This discussion is provided in this section as over a decade ago, a prototype of this model was developed for Virginia. In addition, components within this model could be considered moving forward. We were unable to locate this prototype or determine its usefulness through interviews with stakeholders; however, such efforts can continue and may produce a working model that could be adjusted for climate-related economic analysis.

The model enables researchers to integrate risk assessment and risk management through interdependent processes that involve two key analytical components:

An Input-Output Model for Estimating Regional Cost Impacts of a Disruption. The first model component calculates how a disruption to a set of transportation infrastructure and economic assets in one sector of the economy impacts other sectors and the region as a whole, due to the interdependencies among the economy's business sectors and assets. The model uses the Department of Commerce BEA data to estimate the impacts in the form of two ratios in the region subsequent to a disruption:

- The inoperability metric: defined as the normalized production loss representing the ratio of unrealized production with respect to "as-planned" production level (calculated on a scale of 0 to 100, representing the share of planned origin-destination trips disrupted, with the scale 0 representing "operations as planned," and 100 as total loss of network functionalities).
- The economic loss metric: a metric representing the value of monetary loss associated with an inoperability value. Such a loss includes reduced demand/supply for the goods and services delivered by the transportation mode/sector whose operations were disrupted, including direct and indirect loss of revenue and productivity.

Hierarchical Holographic Modeling (HHM). This model component captures the influence of the multiple dimensions of disruption reflecting the interdependencies among the sectors —power, transportation, communications, business sector, and supply chains—that influence the transportation network and operations. Risk Filtering, Ranking, and Management Method (RFRM), is a component of the HHM modeling framework that identifies, prioritizes, assesses, and manages risks to complex, large-scale systems (see adjacent textbox).

[227] Haimes (2004).

Risk filtering enables decision-makers to focus on the sources of risk that are most critical. Next the prioritized risks are further considered in the risk management (RM) phase, where potential policy options are evaluated for implementation. Finally, during the last phase of the process, the operational feedback are addressed through an iterative process of reviewing and improving the analysis derived from prior phases.

RFRM encapsulates the six questions of risk assessment and management:

- What can go wrong?
- What is the likelihood that it would go wrong?
- What are the consequences?
- What can be done? What options are available?
- What are the associated tradeoffs in terms of all costs, benefits, and risks?
- What are the impacts of current management decisions on future options?

PART 3 – NEXT STEPS IN CONDUCTING AN ECONOMIC QUANTIFICATION STUDY IN THE HR REGION

There are two key principles that guide the next steps in conducting an economic quantification regarding the transportation network in the HR region: (1) the need for national replicability; and (2) delivering value to HR stakeholders. DOT's objective for the Hampton Roads Climate Impact Initiative includes supporting a regional-scale pilot once data and methodologies are validated at the local level, through the following tasks, as follows:

- Task 2: Determining a methodology for estimating future costs using different scenarios and time scales;
- Task 3: Conducting a small-scale pilot analysis using different scenarios and time scales; and
- Task 4: Conducting a region-scale using different scenarios and time scales.

First, given DOT's role assisting states and MPOs nationwide, this Initiative will enable broader intergovernmental coordination on transportation planning, not only to bolster the quantification tools available to government, industry and the public in Hampton Roads, but eventually to other vulnerable regions nationwide. Second, DOT strives to timely add value to ongoing research efforts in the HR region through continued and sustained outreach to regional parties engaged in research on the direct and indirect impacts of SLR and storm surge on transportation networks. For example, DOT is aware of efforts including: follow on work from the HR Intergovernmental Pilot; the Joint Land Use Study funded by the Navy; and HRTPO's 2016 study on roadways, discussed in this section below. Collaboration within HR will ensure this work builds on existing efforts, while avoiding duplication. To that end, DOT continues to travel to the HR region and regularly communicate with governmental and industry representatives concerned with transportation matters.

The economic models described in this report will be evaluated, in consultation with our stakeholders, to determine which model or models is/are best suited for analysis of discrete asset components and network-wide transportation system based data availability and the indirect consequences of interest, as discussed in Part 1 of this report. Testing may include various scenarios such as the impacts associated with recurrent flooding, a baseline-event, recurrent flooding under future SLR, a future-event, a future-event accounting for potential future projects, and a future-event with a suite of adaptation measures. For instance, HRPTO developed three future coastal flood scenarios for the 2045 time-frame for potential use in their Long Range Transportation Plan that are accepted by the community and are available in GIS layers.[228] These layers could potentially serve as a jumping off point for this analysis. Examples of possible pathways for moving forward are described below:

[228] HRTPO (2016).

- If coastal inundation from a storm event were to occur under present conditions, what are the direct and indirect economic implications associated with simulated disruptions in the transportation system for HR? Through economic impact analysis, the direct and indirect economic costs associated with study-wide transportation asset losses can be estimated. These baseline-event-impacted-assets represent a collection of assets where strategies to reduce impact could be considered as "no regrets." A present conditions analysis could answer specific questions, such as: Which economic methodology is most appropriate for this analysis? Are there specific industries most affected by transportation loss (e.g., tourism, shipping, etc.)? Are specific neighborhoods or corridors adversely affected by transportation loss that contribute to a greater loss to the economy or experience a greater loss to income? Are utilities concerned that flooded corridors will prevent them from servicing downstream customers? Are there specific transportation modes that are more greatly affected (and if so, are there interconnectivities/redundancies across modes that can compensate for this)?

- The event-driven economic analysis can be manipulated to draw out those transportation assets that are linked to the greatest potential regional costs, which can serve as an economic-based criticality tool, opposed to currently used criticality evaluation processes. Economic impact may overlap with existing criticality metrics such as redundancy where more built-in redundancy a system possesses, the less the economic consequence by loss of asset. A qualitative comparison can then be drawn as to whether this economic-based criticality tool targets different assets than would be identified through processes currently used within the HR Pilot and USDOT Gulf Coast Phase 2 study to illustrate the value-added by considering economic consequences.

- The economic impact analysis described in the first bullet could be repeated under one or more future scenarios of coastal inundation to capture additional assets, or at a broader scale, groups of assets that comprise a supply chain or strategic route for a key segment (e.g., intermodal freight shipments), that may be exposed under a changing climate and associated SLR, change in storm inundation, etc. These additional assets can be tagged with a "future-event-impacted-assets" identification (as opposed to the "currently-at-risk assets" identified in Step 1). These assets appear to function adequately under today's conditions but may not in the future due to changes in climate. Questions that could be considered: Is the economic impact analysis methodology still appropriate and robust under future scenarios? Does the future scenario economic modeling suggest significant increases in economic consequences of an equivalent event occurring under future climate conditions compared to today's conditions? Does the future scenario suggest a shift in industries or neighborhoods affected? Are there planned projects that would introduce redundancy into the system that will reduce the impact of loss of service?

- Of transportation assets that are most critical for the economic vitality of the region, what are the most cost-effective adaptation strategies? Simulated implementation of these strategies within the

economic analysis would allow for an understanding of how planning could strengthen the future resilience within the region to particular types of events.

DOT may draw from its DOT Volpe Resilience Framework when conducting a full-scale analysis of the Pilot region's transportation risks and potential adoption of cost-effective mitigation and adaptation measures. The DOT Volpe risk-based framework defines resilience as the byproduct of an infrastructure system's capacity to anticipate potential risks, monitor and detect threats, adapt, reorganize and absorb damages, and respond to disturbance by mitigating the harm and restoring essential functions to ensure operational continuity (see Figure 45).[229] Embedded in the DOT Volpe Center Resilience Framework is a rigorous, proactive decision-support perspective that views risk management and adaptation planning within the context of systematic risk mitigation and portfolio-investment planning. For such a future pilot study, these adaptation components can be considered within the DOT and FHWA Framework for Vulnerability Assessment.

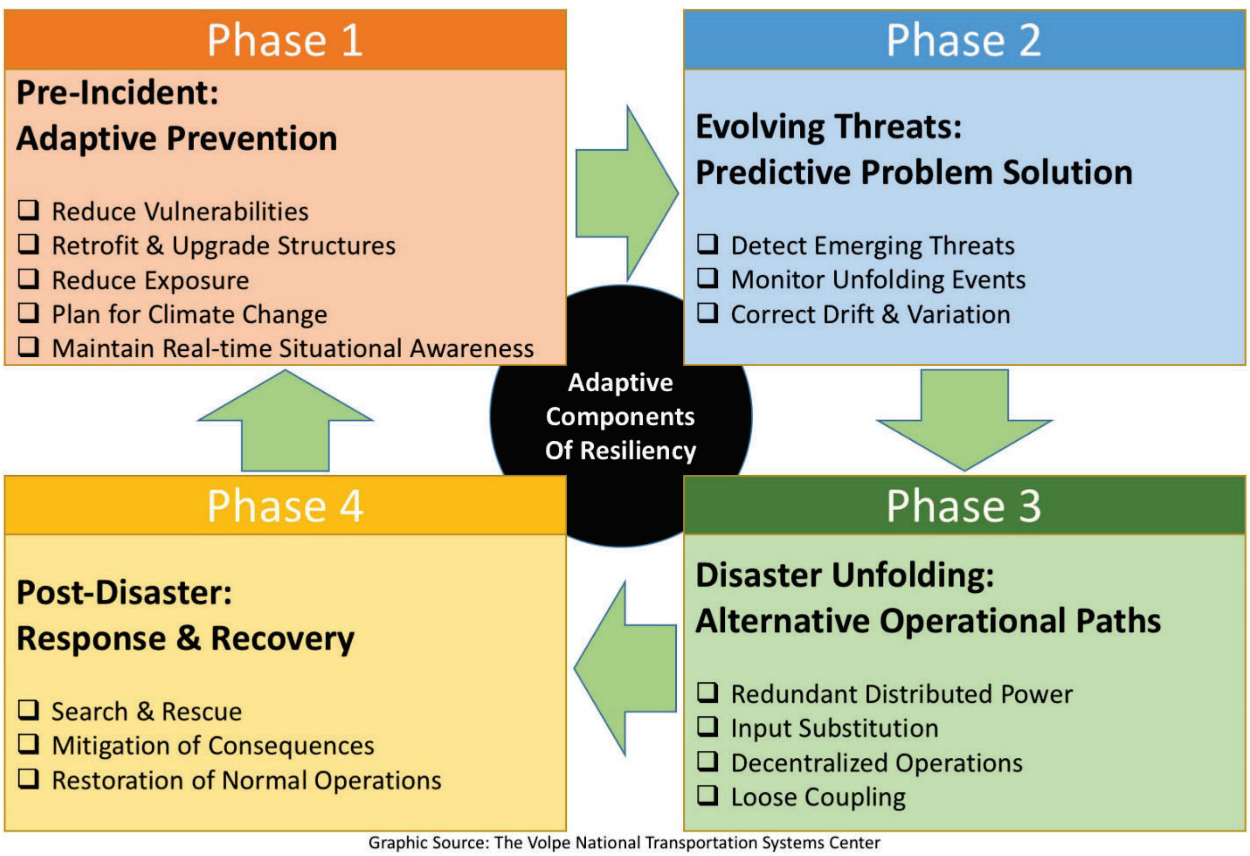


Figure 45. Adaptation components of the DOT Volpe Center Resilience Framework (Source: Volpe Center (2013)). This illustration depicts the application of adaptive measures for reducing the risks to a complex infrastructure system through a lifecycle process of preventive pre-event structural adaptation actions as well as post event mitigation measures.

[229] Volpe Center (2013).

APPENDIX A – ACRONYMS

AMS	Asset Management System
BEA	Bureau of Economic Analysis
CAPTA	Costing Asset Protection for Transportation Agencies
CASI	Climate Adaptation Science Investigator
CGE	Computable General Equilibrium
CIP	Capital Improvement Plan
CIRA	Climate Impacts and Risk Analysis
COLI	Cost of Living Index
CRMES	Center for Risk Management of Engineering Systems
DOC	Department of Commerce
DOE	Department of Energy
DOT	Department of Transportation
EIAC	Economic Impact Advisory Committee
EPA	Environmental Protection Agency
ERDC	US Army Engineers R&D Center
FAA	Federal Aviation Administration
FAF	Freight Analysis Framework
FEMA	Federal Emergency Management Administration
FHWA	Federal Highway Administration
FTZ	Foreign Trade Zone
GDP	Gross Domestic Product
GIS	Geographic Information System
GSP	Gross State Product
HAZUS-MH	Hazards United States – Multi-Hazard
HMA	Hazard Mitigation Assistance
HR	Hampton Roads
HRPDC	Hampton Roads Planning District Commission
HRTPO	Hampton Roads Transportation Planning Organization
IMPLAN	Impact Analysis for Planning
I-O	Input-Output
IPCC	Intergovernmental Panel on Climate Change
IWG	Infrastructure Working Group
LRTP	Long Term Transportation Plan
MCDA	Multi-Criteria Decision Analysis
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
NASA	National Aeronautics and Space Administration
NCADAC	National Climate Assessment and Development Advisory Committee
NCDC	National Climate Data Center

NCHRP	National Cooperative Highway Research Program
NIT	Norfolk International Terminal
NOAA	National Oceanic and Atmospheric Administration
NHC	National Hurricane Center
NNMT	Newport News Marine Terminal
NS	Norfolk Southern
NWS	National Weather Service
ODU	Old Dominion University
ORF	Norfolk International Airport
POV	Port of Virginia
R&R	Response and Recovery
REAcct	Regional Economic Accounting
RIMS II	Regional Input-Output Multiplier System
SHELDUS™	Spatial Hazard Events and Losses Database for the US
SLOSH	Sea, Lake, and Overland Surges for Hurricanes
SLR	Sea-Level Rise
SoVI	Social Vulnerability Index
SOW	Statement of Work
TAM	Transportation Asset Management
TAZ	Traffic Analysis Zone
TCC	Traffic Control Center
TEU	Twenty Foot Equivalent Unit
TMC	Traffic Management Center
VAST	Vulnerability Assessment Scoring Tool
VDOT	Virginia Department of Transportation
VIMS	Virginia Institute of Marine Science
USACE	U.S. Army Corps of Engineers
USGCRP	U.S. Global Climate Research Program

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*Indicates source was used in Table 44

APPENDIX C – DATA SOURCES AND DATABASE DESCRIPTIONS

Data Source	Data Obtained
HAZUS-MH	Hazards-US, Multi-hazard software (HAZUS-MH), a GIS-based loss estimation tool, uses a nationally applicable standardized methodology that estimates potential losses from earthquakes, hurricane winds and floods. The Federal Emergency Management Agency (FEMA) developed HAZUS-MH under contract with the National Institute of Building Sciences (NIBS) HAZUS-MH allows the user to map and display hazard data and the results of damage and economic loss estimates for buildings and infrastructure. It also allows users to estimate the impacts of earthquakes, hurricane winds, and floods on populations. HAZUS-MH contains valuation estimates for transportation infrastructure components. However, except for bridges it does not estimate potential damages to those components due to hazard events. https://www.fema.gov/hazus.
Spatial Hazard Events and Losses Database for the United States (SHELDUS ™)	SHELDUS is a county-level hazard data set for the U.S. and includes 18 different natural hazard events types such thunderstorms, hurricanes, floods, wildfires, and tornados. The database covers the period from January 1960 to December 2014. It contains information on the date of an event (beginning and end), affected location (county and state) and the direct losses caused by the event (property and crop losses, injuries, and fatalities). The Hazard and Vulnerability Research Institute at the University of South Carolina manages SHELDUS ™ http://hvri.geog.sc.edu/SHELDUS/. http://webra.cas.sc.edu/hvri/products/sheldusmetadata.aspx.
NOAA	In addition to meteorological data on sea level rise and flooding frequency, NOAA has also developed a range of impact estimating models and databases in its National Centers for Environmental Information (NCEI) documenting a range of climate-related events in the U.S. The storm events database currently contains data from January 1950 to September 2015, as entered by NOAA's National Weather Service (NWS). Due to changes in the data collection and processing procedures over time, there are unique periods of record available depending on the event type. http://www.ncdc.noaa.gov/. https://www.ncdc.noaa.gov/stormevents/.
USACE Data on Ports	The USACE Navigation Data Center maintains a database of over 40,000 port-and-waterway facilities and other navigation points of interest. The data describe the physical and inter-modal (infrastructure) characteristics of the coastal, Great Lakes, and inland ports of the United States. The data include, but are not limited to: location (latitude/longitude, waterway, mile, and bank); operations (name, owner, operator, purpose, handling equipment, rates, and details of open-and-covered storage facilities); type and dimension of construction (length of berthing space for vessels and/or barges, depth, apron width, deck elevation, and details of rail-and-highway access); and utilities available (water, electricity, and fire protection).USACE data on ports are available as GIS shapefiles. The point features include attributes such as dock construction type and material, owner, and use. www.navigationdatacenter.us/ports/ports.htm.

Data Source	Data Obtained
National Bridge Inventory (NBI)	The NBI contains codes for over 130 items related to bridges. It includes identifying information, structural information, condition information, usage information, and more. The data are available at the FHWA website, as is the coding guide that explains what is being rated and what the codes mean. Some of the items used in the report include structure type, average daily traffic, scour rating, and deck condition. http://www.fhwa.dot.gov/bridge/nbi.cfm. http://www.fhwa.dot.gov/bridge/mtguide.pdf.
National Transportation Atlas Database (NTAD)	The NTAD is a set of nationwide geographic databases of transportation facilities, transportation networks, and associated infrastructure. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/index.html.

APPENDIX D – SUPPORTING INFORMATION AND TERMINOLOGY

HRTPO Prioritization Tool and Scoring Criteria for Economic Vitality[230]

Highway projects:

ECONOMIC VITALITY	
Total Reduction in Travel Time	**30.00**
Labor Market Access	**20.00**
Increase Travel Time Reliability	*10.00*
Increased Access for High Density Employment Areas	*10.00*
Addresses the Needs of Basic Sector Industries	**30.00**
Increases Access for Port Facilities	*10.00*
Increases Access to Tourist Destinations	*10.00*
Increases Access for Defense Installations	*6.00*
Facility part of STRAHNET	*4.00*
Facility part of "Roadways Serving the Military"	*3.00*
Increased Opportunity	**20.00**
Provides New of Increased Access	*10.00*
Supports Plans for Future Growth	*10.00*
ECONOMIC VITALITY TOTAL	***100.00***

Interchange projects:

ECONOMIC VITALITY	
Total Reduction in Travel Time	**30.00**
Labor Market Access	**20.00**
Increase Travel Time Reliability	*10.00*
Increased Access for High Density Employment Areas	*10.00*
Addresses the Needs of Basic Sector Industries	**30.00**
Increases Access for Port Facilities	*10.00*
Increases Access to Tourist Destinations	*10.00*
Increases Access for Defense Installations	*6.00*
Facility part of STRAHNET	*4.00*
Facility part of "Roadways Serving the Military"	*3.00*
Increased Opportunity	**20.00**
Provides New of Increased Access	*10.00*
Supports Plans for Future Growth	*10.00*
ECONOMIC VITALITY TOTAL	***100.00***

[230] HRTPO (2013c).

Bridge and tunnel projects:

ECONOMIC VITALITY	
Total Reduction in Travel Time	**30.00**
Labor Market Access	**20.00**
Increase Travel Time Reliability	*10.00*
Increased Access for High Density Employment Areas	*10.00*
Addresses the Needs of Basic Sector Industries	**30.00**
Increases Access for Port Facilities	*10.00*
Increases Access to Tourist Destinations	*10.00*
Increases Access for Defense Installations	*6.00*
Facility part of STRAHNET	*4.00*
Facility part of "Roadways Serving the Military"	*3.00*
Increased Opportunity	**20.00**
Provides New of Increased Access	*10.00*
Supports Plans for Future Growth	*10.00*
ECONOMIC VITALITY TOTAL	***100.00***

Transit projects:

ECONOMIC VITALITY	
Labor Market Access	**45.00**
Increases Access for Major Employment Centers	***20.00***
Increases Travel Time Reliability	***10.00***
Increases Frequency of Service	***10.00***
Provides Access to Institutions of Higher Education	***5.00***
Addresses the Needs of Basic Sector Industries	**20.00**
Provides or Improves Access for Defense Installations	***10.00***
Provides/Improves Access for Tourist Destinations	***10.00***
Increased Opportunity - Provides New Access to the Network	**20.00**
Provides New Access to the Network	***5.00***
Supported by Plans for Increased Density and Economic Activity	***15.00***
Economic Distress Factors	**15.00**
Provides Access to Areas with High Unemployment	***5.00***
Provides Access to Low Income Areas	***10.00***
ECONOMIC VITALITY TOTAL	***100.00***

Intermodal projects:

ECONOMIC VITALITY	
Total Reduction in Travel Time	**20.00**
Labor Market Access	**35.00**
Increase Travel Time Reliability	*15.00*
Impact on Truck Movement	*15.00*
Increased Access for High Density Employment Areas	*5.00*
Addresses the Needs of Basic Sector Industries	**15.00**
Increases Access for Port Facilities	*5.00*
Improves Flow of Rail	*5.00*
Increases Access to Air	*5.00*
Increased Opportunity	**30.00**
Provides New of Increased Access	*20.00*
Supports Plans for Future Growth	*10.00*
ECONOMIC VITALITY TOTAL	***100.00***

HAZUS-MH Valuation Formulas

Table 3.21 Highway System Classifications

Flood Label	General Occupancy	Specific Occupancy	Hazus Valuation[1]
HRD1	Highway Roads	Major Roads (1km 4 lanes))	10,000
HRD2	Highway Roads	Urban Roads (1 km 2 lanes)	5,000
HTU	Highway Tunnel	Highway Tunnel	20,000
HWBM	Highway Bridge	Major Bridge	20,000
HWBO	Highway Bridge	Other Bridge (include all wood)	1,000
HWBCO	Highway Bridge	Other Concrete Bridge	1,000
HWBCC	Highway Bridge	Continuous Concrete Bridge	5,000
HWBSO	Highway Bridge	Other Steel Bridge	1,000
HWBSC	Highway Bridge	Continuous Steel Bridge	5,000

Notes:

1 All dollar amounts are in thousands of dollars.

Table 3.22 Railway System Classifications

Flood Label	General Occupancy	Specific Occupancy	Hazus Valuation[1]
RTR	Railway Tracks	Railway Tracks (per km)	1,500
RBRU	Railway Bridge	Railway Bridge Unknown	5,000
RBRC	Railway Bridge	Concrete Railway Bridge	5,000
RBRS	Railway Bridge	Steel Railway Bridge	5,000
RBRW	Railway Bridge	Wood Railway Bridge	5,000
RTU	Railway Tunnel	Railway Tunnel	10,000
RSTS	Railway Urban Station	Steel Railway Urban Station	2,000
RSTC	Railway Urban Station	Concrete Railway Urban Station	2,000
RSTW	Railway Urban Station	Wood Railway Urban Station	2,000
RSTB	Railway Urban Station	Brick Railway Urban Station	2,000
RFF	Railway Fuel Facility	Railway Fuel Facility (Tanks)	3,000
RDF	Railway Dispatch Facility	Railway Dispatch Facility (Equip)	3,000
RMFS	Railway Maintenance Facility	Steel Railway Maintenance Facility	2,800
RMFC	Railway Maintenance Facility	Concrete Railway Maintenance Facility	2,800
RMFW	Railway Maintenance Facility	Wood Railway Maintenance Facility	2,800
RMFB	Railway Maintenance Facility	Brick Railway Maintenance Facility	2,800

Notes:

1 *All dollar amounts are in thousands of dollars.*

Bridge Standards Discussed in this Report

Functionally Obsolete: a structure that was built to geometric standards that are no longer used today. These bridges do not have adequate lane width, shoulder width, or vertical clearances to serve the current traffic volumes or meet current geometric stands. These bridges may be more likely to be occasionally flooded or have approaches that are difficult to navigate. However, they are not inherently unsafe.

Structurally Deficient Bridges: Bridges are structurally deficient when one or more major components is deteriorating. Structurally deficient bridges need to be monitored or repaired, but are not necessarily unsafe. Transportation agencies will close unsafe bridges.

Deficient Bridges: Defined as the combination of structurally deficient and functionally obsolete bridges. This category has historically been used to determine eligibility for federal funding. [Combines Structural and Functional deficiency]

Weight-posted Bridges: These bridges are defined as structures that have a rated load-carrying capacity that is less than the designated legal truck weights in the state of VA (where the maximum legal truck weigh is 27 tons for a 3-axle single unit vehicle and 40 tons for trucks with semi-trailers. A total of 102 bridges in HR (8.3%) have posted weight restrictions, ranking 11th among comparable metro areas.

Fracture and Scour Critical Bridges: Two types of structure require more monitoring than typical bridges due to their design or location: Fracture Critical structures and bridges that are Vulnerable to Scouring. Most bridges are designed so that loads of can be redistributed to other structural members if any one structural member loses its ability to distribute loads. However, fracture critical bridges are structures that are designed with few or no redundant supporting elements and are in danger of collapsing if a key structural member fails. Despite this lack of redundancy, however, fracture critical bridges are not necessarily unsafe. They, however, undergo more extensive and more frequent inspections, usually on an annual basis. Examples of FC bridges are most truss bridges, drawbridges, and those beam or girder bridges designed without redundant elements.

Scour Critical Bridges: Bridges with underwater substructure sections may be vulnerable to scouring, i.e., the exposure of portions of the substructure due to changes in the riverbed. In cases where a bridge is a risk of failure due to scouring, they are inspected more frequently (every 5 years) to assure that the potentially vulnerable ones do not in fact become scour critical. Currently no bridges in HR are classified as such.

Table D-1. Scour Critical Bridges codes (Source: *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*)

Code	Description
N	Bridge not over waterway.
U	Bridge with "unknown" foundation that has not been evaluated for scour. Since risk cannot be determined, flag for monitoring during flood events and, if appropriate, closure.
T	Bridge over "tidal" waters that has not been evaluated for scour, but considered low risk. Bridge will be monitored with regular inspection cycle and with appropriate underwater inspections. **("Unknown" foundations in "tidal" waters should be coded U.)**
9	Bridge foundations (including piles) on dry land well above flood water elevations.
8	**Bridge foundations determined to be stable for assessed or calculated scour conditions; calculated scour is above top of footing.**
7	Countermeasures have been installed to correct a previously existing problem with scour. Bridge is no longer scour critical.
6	Scour calculation/evaluation has not been made. (Use only to describe case where bridge has not yet been evaluated for scour potential.)
5	**Bridge foundations determined to be stable for calculated scour conditions; scour within limits of footing or piles.**
4	**Bridge foundations determined to be stable for calculated scour conditions; field review indicates action is required to protect exposed foundations from effects of additional erosion and corrosion.**
3	Bridge is scour critical; bridge foundations determined to be unstable for calculated scour conditions: - Scour within limits of footing or piles. - Scour below spread-footing base or pile tips.
2	**Bridge is scour critical; field review indicates that extensive scour has occurred at bridge foundations. Immediate action is required to provide scour countermeasures.**
1	Bridge is scour critical; field review indicates that failure of piers/abutments is imminent. Bridge is closed to traffic.
0	**Bridge is scour critical. Bridge has failed and is closed to traffic.**

Table D-2. Countermeasure costs for each countermeasure "hard-wired" into the CAPTool (source: CAPTool spreadsheet)

Countermeasure Category	Countermeasure	ESTIMATED PER-UNIT COST (x1000)	Comments	Unit of measure
Physical Security Countermeasures	Lighting	11.3	one per 100 feet of road or perimeter. Assumes nearby power connection, no demolition or excavating.	1
	Barriers & Berms	3.3	10 jersey barriers and two end planters to cover 100 feet of space	1
	Fences	21	12 foot height security fence, in concrete with 4 gates (6 feet high, 3 feet wide). Infrared detection system. Power install, relay to central monitor. Excludes central monitoring station operation.	100 linear feet
	CCTV	17.5	4 remote PTZ cameras, one control panel	1
	Intrusion Detection Devices	0.9	1 burglar alarm with remote signal installed	1
	Physical Inspection of asset	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE employee per year
Access Control Countermeasures	ID Cards	10	6 zone system with database, installed	6 zones
	Biometrics	50	6 facial and fingerprint scanners, database, installed	6 zones
	Background Checks	57	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Metal Detectors	138	6 portals, 4 handhelds, installed. Assumes no demolition and nearby power source	
	Restricted Parking	18.45	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Random Inspections	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Visible Badges	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Limited Access Points	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Visitor Control & Escort	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Locks	1.2	1 cipher lockset, installed. Assumes no demolition or heavy construction	Each
	Explosive Detection	257	2 portals, 2 handhelds, with power	2+2
	Establish Clear Zones	0.1	100 sq yards. Assumes no demolition	100-SY
	Visible Signs	0.09	1 aluminum sign 18 inches high, with base	Each
Asset Design/Engineering	Seismic Retrofitting	10000	Estimates must be changed to reflect local variation	Per application
	Fire Detection & Supression	459.992	Class III standpipe system with Type 2 water supply to 10,000 sf building. System includes minimum 20 pull stations with master box, annunciator, and central station relay. Assumes minimal demolition.	
	Encasement, Wrapping, Jacketing	0.6	Estimates must be changed to reflect local variation	100-SF
Operational Countermeasures	Patrols	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	WX/Seismic Information	100	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Intelligence Networking	100	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	HAZMAT Mitigation	1329.6	Assumes complete start up of hazmat remediation program providing 24 hour coverage. Mechanized crew of 8 persons. Excludes material dumping costs	1crew
	Security Awareness Training	100	Contracted	1 program
	Emergency Response Training	100	Contracted	1 program
	Emergency Evacuation Planning	100	Designed program for structures and stations	1 program
	Planned Redundancy (e.g., detours)	220	Pre-staged and marked detours. Deploys one FT traffic engineer, 1 PT carpenter, 1 PT operating engineer,	$9,000 fixed cost - $211,000 per year
	Public Information and Dissemination	150	1 PIO, 1 web technician.	2 FT employee per year

HRPDC Asset Value Methodology

The HRPDC methodology for estimating the number of businesses impacted by SLR risks was based on the individual businesses' location data collected from ESRI's Business Analysis suite. This business layer was spatially joined to a locality boundary layer to give business a county/city identifier. The data layer was overlaid on top of each SLR vulnerability zone. The total number of businesses and employees was calculated for each scenario for all 16 HR localities and the region as a whole. Parcel information was also used to

represent the economic impact: i.e., the total value of each parcel as representing investments in real property.[231]

Two key metrics in the 2012 Phase III HRPDC report are helpful for estimating the economic impacts of the potential damages to the transportation infrastructure: the "Improvement Value" of the parcels within the region's "Built Environment" and the "Total value of the parcels." Improvement values are the value of buildings and other non-land improvements on those properties (a measure of how much "immovable" property is exposed). While improvement value indicates how much has been built at a given location, total value indicates the market value of the whole property. In many vulnerable areas, land values are higher than improvement values, since waterfront property is highly desirable.

VAST Tables of Sensitivity and Adaptive Capacity

Table D-3. List of sensitivity indicators provided in the sensitivity indicator library (Source: VAST Tool)

Roads	Bridges	Rail lines	Ports	Airports	Transit
Temperature					
- Past Experience with temperature - Truck Traffic - Temperature Threshold in Pavement Binder - Thermal Expansion Coefficient of Concrete - Condition of Concrete Pavement Joints - Presence of Bus Routes - Use of Polymer Modified Binders	- Past Experience with temperature - Truck Traffic - Temperature Threshold in Pavement Binder - Thermal Expansion Coefficient of Concrete - Condition of Concrete Pavement Joints - Presence of Bus Routes - Use of Polymer Modified Binders	- Past Experience with Temperature - Rail Design - Maintenance Frequency - Ballast Type - Shade - Rail-neutral Temperature - Rail Curvature - Permafrost	- Past Experience with Temperature - Size of Paved Asphalt Areas - Reliance on Electrical Power - Materials Handled - Frequency of Breaks - Safety Regulation Threshold	- Past Experience with Temperature - Runway Surface Pavement Type - Runway Condition - Runway Length - Airport Elevation - Thermal Expansion Coefficient of the Concrete - Condition of Concrete Pavement Joints - Use of Warm-Mix Asphalt - Use of Polymer Modified Binders	- Past Experience with Temperature - Age of Buses

[231] (Note: HRPDC III does not include shoreline and flood protection infrastructure; to this extent, the results may best be interpreted as general baseline estimates of SLR in the absence of adaptation measures.)

Heavy Precipitation					
- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Proximity to Coast	- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Approach Elevation - Bridge Age - Scour Rating - Channel Condition - Culvert Condition - Frequency that Water Overtops Bridge - Proximity to Coast	- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Undercut Track - Ballast Type - Electric Signals - Soil Type - Maintenance Frequency - Condition of Drainage System - Materials Used in Drainage System - Design Capacity of Drainage System - Age of Drainage System	- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Age of Wharves, Structures - Materials Handled - Sediment Buildup - Materials Sensitive to Freezing - Condition of Drainage System - Design Capacity of Drainage System	- Past Experience with Precipitation - Age of Drainage System - Drainage System Pipe Condition - Evidence of Blowouts - Propensity for Ponding - Percentage of Impervious Surface - Airport Traffic/Congestion Levels - Soil Type - Runway Condition - Surface Treatment - Approach Lights - Instrumentation Type	- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Impaired Assets - Ventilation/ Tunnel Openings in Flood-Prone Areas - Flood Protection
Sea Level Rise					
- Past Experience with Tides/SLR - Flood Protection - Soil Type - Nearby Areas Exposed to SLR	- Past Experience with Tides/SLR - Approach Elevation - Navigational Clearance of Bridge - Bridge Height - Soil Type - Nearby Areas Exposed to SLR	- Past Experience with Tides/SLR - Drainage System Performance - Elevation - Soil Type - Protection	- Past Experience with Tides/SLR - Shoreline Protection - Age of Wharves, Structures - Elevation Relative to Sea Level - Height of Drainage Outlets Relative to Sea Level - Floating or Fixed - Type of Operations	- Past Experience with Tides/SLR - Height of Drainage Discharge - Drainage System Pipe Condition - Evidence of Blowouts - Age of Drainage System - Adjacent to Areas Exposed to Sea Level Rise - Access Roads Vulnerable to Sea Level Rise	- Past Experience with Tides/SLR - Elevated or Protected above Bare Earth Elevation - Impaired Access - Ventilation/ Tunnel Openings in Flood-Prone Areas - Flood Protection

Storm Surge					
- Past Experience with Storm Surge Flood Protection - Elevation of Asset	- Past Experience with Storm Surge - Bridge Height - Navigational Clearance of Bridge - Scour Rating - Condition of Bridge Substructure - Condition of Bridge Superstructure - Condition of Bridge Deck - Movable Bridge - Bridge Age - Approach Elevation - Elevation of Asset - Weight of Bridge Deck - Bridge Deck Type - Number of Longitudinal Girders	- Past Experience with Storm Surge - Drainage System Performance - Elevation or Protection - Undercut Track - Ballast Type - Soil Type - Electric Signals - Elevation of Asset - Materials Used in Drainage System - Design Capacity of Drainage System	- Past Experience with Storm Surge - Shoreline Protection - Height of Key Infrastructure - Age of Wharves, Structures - Condition - Reliance on Electrical Power - Materials Handled - Types of Key Infrastructure - Location of Key Equipment	- Past Experience with Storm Surge - Foundation Type - Drainage System Pipe Condition - Age of Drainage System - Evidence of Blowouts - Soil Type - Approach Lights	- Past Experience with Storm Surge - Foundation Type - Elevated or Protected above Bare Earth Elevation - Impaired Access - Ventilation/ Tunnel Openings in Flood-Prone Areas - Flood Protection
Wind					
- Past Experience with Wind - Roadway Signal Density - Wind Design Speeds - Proximity of Trees to Power Lines - Efficacy of Tree Trimming Maintenance - Building Density - Presence of Overhead Utility Lines - Sign Support Strength - Height and Size of Road Signs - Length of Support Arms	- Past Experience with Wind - Roadway Signal Density - Wind Design Speeds - Proximity of Trees to Power Lines - Efficacy of Tree Trimming Maintenance - Building Density - Presence of Overhead Utility Lines - Sign Support Strength - Height and Size of Road Signs - Length of Support Arms - Fixed of Cabled Signals?	- Past Experience with Wind - Number of Signals/Signs or Major Crossings - Presence of Ariel Signal Lines - Proximity of Trees to Power Lines - Efficacy of Tree Trimming Maintenance - Building Density - Presence of Overhead Utility Lines - Sign Support Strength - Height and Size of Road Signs - Length of Support Arms	- Past Experience with Wind - Age of Wharves, Structures - Reliance on Electrical Power - Materials Handled - Wind Design Speeds - Port Equipment - Nearby At-Risk Infrastructure	- Past Experience with Wind - Age of Buildings - Building Material Type - Roof Type - Height of Air Traffic Control Tower - Height of Hangers - Height of Terminals - Sheltered by Surrounding - Wind Design Speeds Operations - Proximity to Projectile Materials	- Past Experience with Wind - Age of Buildings or Fleet - Building Material Type - Roof Type - Building Height - Sheltered by Surrounding Structures - Wind Design Speeds

- Fixed of Cabled Signals? - Underground or Overhead Power and Utilities?	- Underground or Overhead Power and Utilities?	- Fixed of Cabled Signals? - Underground or Overhead Power and Utilities?			

Table D-4. List of sensitivity indicators provided in the adaptive capacity indicator library (Source: VAST Tool)

Roads	Bridges	Rail lines	Ports	Airports	Transit
Replacement Cost	Replacement Cost	Presence of Bridges along Segment	Redundancy within a Facility	Special Designation	Priority for Assistance
Detour Length	Detour Length	Signaling	Redundancy across Facilities	Number of Terminals	Function or Facility Asset
Disruption Duration	Disruption Duration	Evacuation Plans	Disruption Duration	Number of Runway Headings	Disruption Duration
FHWA Roadway Functional Classification	FHWA Roadway Functional Classification	Part of Disaster Relief Recovery Plan	Availability of Supplies and Repair Equipment	Distance to Nearest Alternate Airport	Ability to Reroute
Evacuation Route	Evacuation Route	Ability to Reroute System	Sharing Equipment across Ports, Agencies	Number of Alternate Airports within 120 Miles	Ability of Fixed Lines to Reroute
Annual Average Daily Traffic	Annual Average Daily Traffic	Interchange Utility	Cost of Replacement of Specific Assets	Disruption Duration	Ability to Reroute around Problem Areas
Historical Repair Cost	Historical Repair Cost	Disruption Duration	Historical Cost of Replacement	Cost of Replacement of Specific Assets	Cost of Replacement of Specific Assets

Access to Critical Areas	Access to Critical Areas	Replacement Cost	Usage Statistics	Historical Cost of Replacement	Historical Cost of Replacement
		Number of Rail Lines	Access to Critical Areas	Usage Statistics	
			Tourism Costs	Access to Critical Areas	
			Cost of Disrupted or Increased Shipping Routes	Redundancy in Power Systems	
				Tourism Costs	
				Cost of Disrupted or Increased Shipping Routes	

APPENDIX E – MERGING INSURANCE "KNOW-HOW" WITH TRADITIONAL CLIMATE-RELATED RISK ASSESSMENTS TO QUANTIFY ECONOMIC LOSS

Insurance providers routinely assess financial risk of weather-related events for insurance policies and financial investments. Some of the methodologies and strategies for considering risk management may be transferable and/or informative when considering methodologies for quantifying economic costs associated with event driven impacts on transportation. A sampling of possibilities are presented below as provided by Mr. Steven Kolk* through an interview.

Actuaries Climate Indices (ACI). The Actuaries' Climate Index (ACI) (see: ActuariesClimateIndex.org.) quantifies the change in the frequency of extreme climate from a combination of a handful of extreme events relative to natural variability (i.e., is the change in extremes statistically different that than suggested by past records). The ACI is an overall index from a combination of a handful of component indexes. An example of an ACI index component is the change in monthly high temperatures compared to the historic 90th percentile of monthly high temperatures (i.e., a very hot month). Another example is the Sea Level ACI component which uses tide gauge data to calculate the effective change in sea level compared to the baseline. The overall ACI and its component indices are useful in showing how the frequency of extreme climate-related events have changed over time for a given location (e.g., have heavy precipitation events increased). For estimates of future exposure to climate risk, the ACI could be extended by post-processing and forecasting the climate index components.

Looking at history there does appear to be overlap between ACIs and climate indices used in hazard assessments. For example, the ACI for flooding is the 5-day maximum precipitation event, which is also one of the indices used to indicate future changes in flooding by the climate community.

Mr. Kolk conducted a correlation analysis of ACI index components for Hampton Roads as shown in the table below from 1991 to 2013. There is a strong positive correlation between monthly high temperatures and sea level rise and a strong negative correlation between wind power and sea level rise. This suggests that from 1991 to 2013, the increasingly more frequent hot months have been increasing at a rate somewhat similar to sea level rise. Also, perhaps like a fan blowing wind cools a room in your apartment or home on a hot summer day, the warmer rising seas (again for the 1991 to 2013 period) may be evaporating more moisture into the air and disbursing sea power (hence the negative correlation) most especially when the more extreme winds are blowing. These types of correlations may also be helpful when considering if these climate indices could occur simultaneously - which could potentially compound the realized impacts.

Actuarial Aspects. When considering climate risks, there are a number of actuarial aspects to consider, and more research could help. Facts to bring to bear and consider could be, determining location-specific exposure and sensitivity to coastal inundation from sea level rise. Sensitivity of coastal areas to sea level rise and water inundation will be dependent on such elements as the coastline's slope, aspect (or direction of the slope), state of erosion, and topography. These elements overlap with those identified by the climate community

when conducting climate-risk based hazard assessments; in other words, the insurance industry likely considers the same elements of risk as the climate/hazard assessment community. When considering property damage, Actuaries Climate Risk Index (ACRI) modeling further suggests population is a significant factor explaining SHELDUS damages. Actuaries who build such models work together with a scientists as NOAA who gather and share data, and risk experts.

Table E-1. ACI Component Correlations with the ACI Sea-Level Rise Index from 1991 to 2012

ACI Component Correlations with the ACI Sea-Level Rise Index from 1991 thru 2013									10-Yr Moving Avg. Correlation	
	Lengthy Drought	Heavy Precipitation	**Sea Level Rise**	Soil Moisture	Low Temperatures	High Temperatures	Wind Power		Average Correlation Coefficient	Standard Dev'n of Corr. Coef.
Lengthy Drought	1.000	-0.535	0.140	-0.800	-0.522	0.495	-0.351		-0.779	0.030
Heavy Precipitation	-0.535	1.000	-0.044	0.687	0.430	-0.345	0.271		0.181	0.279
Sea Level Rise	0.140	-0.044	1.000	-0.567	-0.602	0.720	-0.894		1.000	0.000
Soil Moisture	-0.800	0.687	-0.567	1.000	0.681	-0.774	0.720		-0.163	0.058
Low Temperatures	-0.522	0.430	-0.602	0.681	1.000	-0.745	0.751		-0.142	0.456
High Temperatures	0.495	-0.345	0.720	-0.774	-0.745	1.000	-0.811		**0.797**	**0.094**
Wind Power	-0.351	0.271	-0.894	0.720	0.751	-0.811	1.000		**-0.895**	**0.036**

Modeling the Consequences of Climate-Related Events. Insurers use a variety of risk modelers (AIR, ARA, EQECAT and RMS) to build risk modelers of many kinds. These models, like FEMA's HAZUS, estimate damage to buildings from Hurricanes, Storm Surge and Flooding. These models provide estimate of risk in terms of the Average Annual Loss (AAL) (i.e., the expected annual loss per year) and Probable Maximum Loss (PML) (i.e., the largest loss that may occur under a disaster/event) associated with personal and commercial property loss. These kinds of estimates could be used to quantify and rank the exposure of various properties exposed to SLR risk. When such models are built, they most often quantify just the short-term direct impacts of individual events. Modeling firms have begun to apply their modeling skills to also estimate the costs of the indirect aftermath from power recovery costs, business interruption and supply chain delays following bigger events. Both kinds of information may be useful, for example, in the CAPTA tool. This then could identify those populations at greatest risk to consider socioeconomic consequences if these populations whose properties are at greater risk to get flooded are also stranded by loss of transportation services/passable facilities.

A few firms have begun to collect additional information to quantify the indirect consequences of transportation disruption.

* Steve Kolk, ACAS, MAAA, Assistant Vice President of Pricing, American Integrity Insurance Company of Florida

APPENDIX F— LETTER FROM CAPTAIN D.A. VANDERLAY, U.S. NAVY, COMMANDING OFFER, NAVAL FACILITIES ENGINEERING COMMAND, NORFOLK, VA TO ALASDAIR CAIN, CO-CHAIR, U.S. DOT CLIMATE CHANGE CENTER (JULY 1 2016)

DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND, MID-ATLANTIC
9324 VIRGINIA AVENUE
NORFOLK, VA 23511-3095

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JUL 0 1 2016

Alasdair Cain
Co-Chair, U.S. DOT Climate Change Center,
Office of the Secretary of Transportation (OST-R)
1200 New Jersey Avenue SE, Room E33-304,
Washington, DC 20590

Dear Mr. Cain,

SUBJECT: DEPARTMENT OF TRANSPORTATION'S DRAFT HAMPTON ROADS CLIMATE IMPACT QUANTIFICATION INITIATIVE STUDY

Thank you for the opportunity for our agency to provide comments on the draft U.S. Department of Transportation's Hampton Roads Climate Impact Quantification Initiative Scoping Paper and Preliminary Baseline Assessment. The scope of the quantification study is comprehensive and starts to address the transportation and economic risks that the Hampton Roads community faces on a regular basis from recurrent flooding, storm surge, and rising seas. The quantification of these impacts, as demonstrated by the baseline assessment, will ultimately serve as a valuable resource for local, regional, and federal agencies, including the Navy, in developing strategies to mitigate and adapt to these emerging risks. In particular, the study will serve as a resource for the both of the region's two upcoming Joint Land Use Studies (JLUS): Norfolk/Virginia Beach and Portsmouth/Chesapeake.

As part of our review of the baseline assessment, we offer a correction to the population figures listed in the chart included in Section 4-3 "Quantifying the Economic Impacts of SLR on the HR Military and Transportation Sectors: Norfolk Area Military Facilities". Please see below for our corrected population figures:

Norfolk Area Military Facilities	Active Duty FY15	Reserves FY15	Civilian FY15	Contractors FY15
NS Norfolk	42997	1462	13438	7037
JEBLCFS	10422	4547	3222	723
NAS Oceana/Dam Neck	9724	980	2786	3080
NNSY	804	96	9921	1553
NWS Yorktown	1379	186	1103	453
NSA Hampton Roads	6942	445	3266	456
Total for Hampton Roads	**72268**	**7716**	**33736**	**13302**

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Again, we appreciate the opportunity to participate in the review of this important initial effort and look forward to collaborating with US DOT as we move forward with the JLUS projects and other initiatives addressing recurrent flooding. If you have any questions regarding our comments or on future collaboration, please contact Brian Ballard, Regional Community Plans and Liaison Officer, at (757) 341-0264 or brian.p.ballard@navy.mil.

Sincerely,

D. A. VANDERLEY
Captain, Civil Engineer Corps
U. S. Navy
Commanding Officer

14 Human Health

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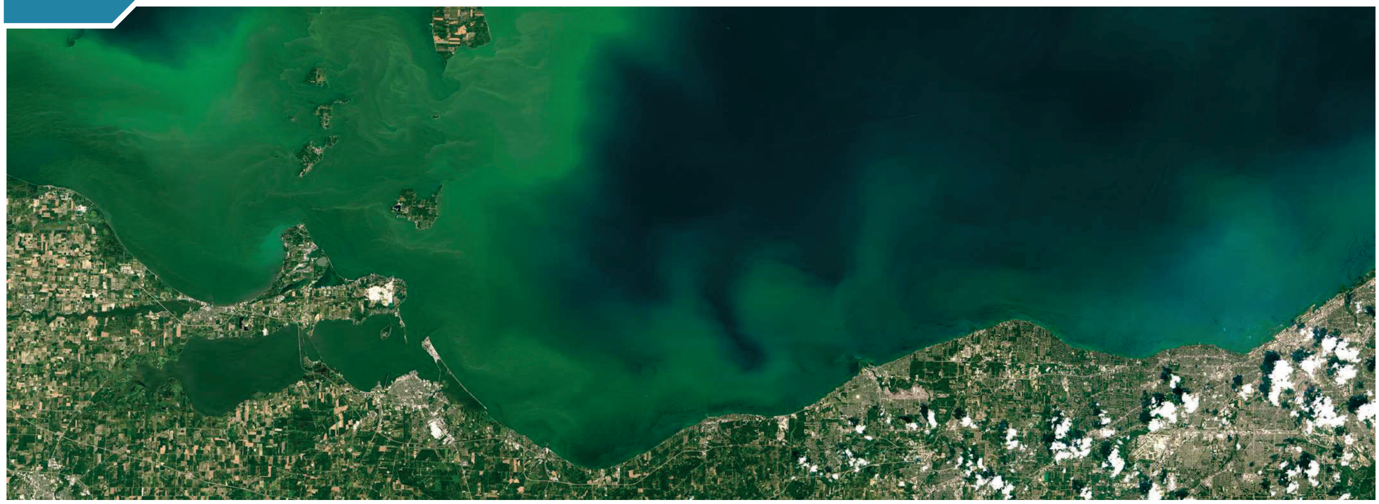
On the Web: https://nca2018.globalchange.gov/chapter/health

14 Human Health



Algal bloom in Lake Erie in the summer of 2015

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Executive Summary

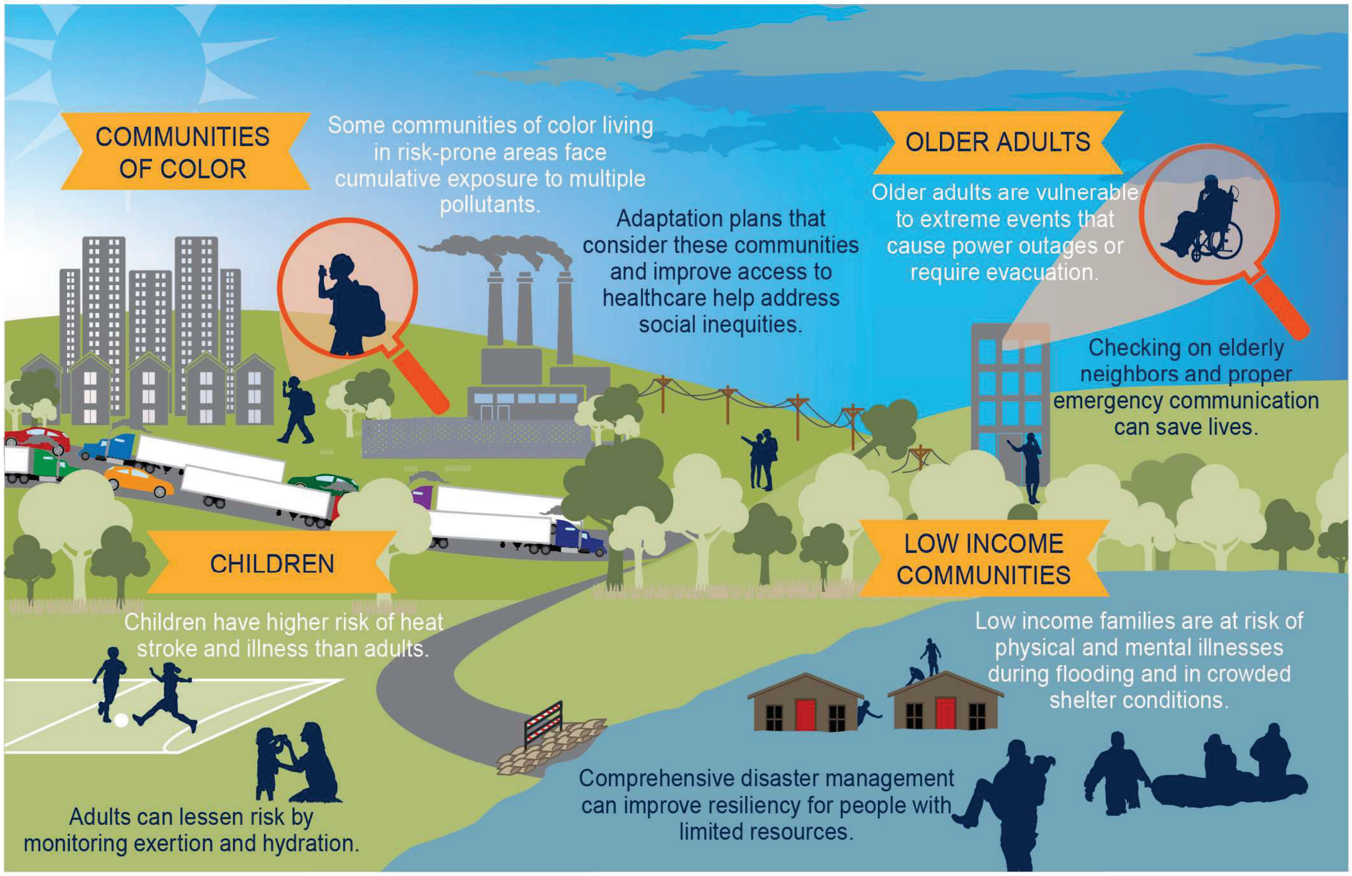
Climate-related changes in weather patterns and associated changes in air, water, food, and the environment are affecting the health and well-being of the American people, causing injuries, illnesses, and death. Increasing temperatures, increases in the frequency and intensity of heat waves (since the 1960s), changes in precipitation patterns (especially increases in heavy precipitation), and sea level rise can affect our health through multiple pathways. Changes in weather and climate can degrade air and water quality; affect the geographic range, seasonality, and intensity of transmission of infectious diseases through food, water, and disease-carrying vectors (such as mosquitoes and ticks); and increase stresses that affect mental health and well-being.

Changing weather patterns also interact with demographic and socioeconomic factors, as well as underlying health trends, to influence the extent of the consequences of climate change for individuals and communities. While all Americans are at risk of experiencing adverse climate-related health outcomes, some populations are disproportionately vulnerable.

The risks of climate change for human health are expected to increase in the future, with the extent of the resulting impacts dependent on the effectiveness of adaptation efforts and on the magnitude and pattern of future climate change. Individuals, communities, public health departments, health-related organizations and facilities, and others are taking action to reduce health vulnerability to current climate change and to increase resilience to the risks projected in coming decades.

The health benefits of reducing greenhouse gas emissions could result in economic benefits of hundreds of billions of dollars each year by the end of the century. Annual health impacts and health-related costs are projected to be approximately 50% lower under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5). These estimates would be even larger if they included the benefits of health outcomes that are difficult to quantify, such as avoided mental health impacts or long-term physical health impacts.

Vulnerable Populations



Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. *From Figure 14.2 (Source: EPA).*

A comprehensive assessment of the impacts of climate change on human health in the United States concluded that climate change exacerbates existing climate-sensitive health threats and creates new challenges, exposing more people in more places to hazardous weather and climate conditions.[1] This chapter builds on that assessment and considers the extent to which modifying current, or implementing new, health system responses could prepare for and manage these risks. Please see Chapter 13: Air Quality for a discussion of the health impacts associated with air quality, including ozone, wildfires, and aeroallergens.

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Climate Change and Health

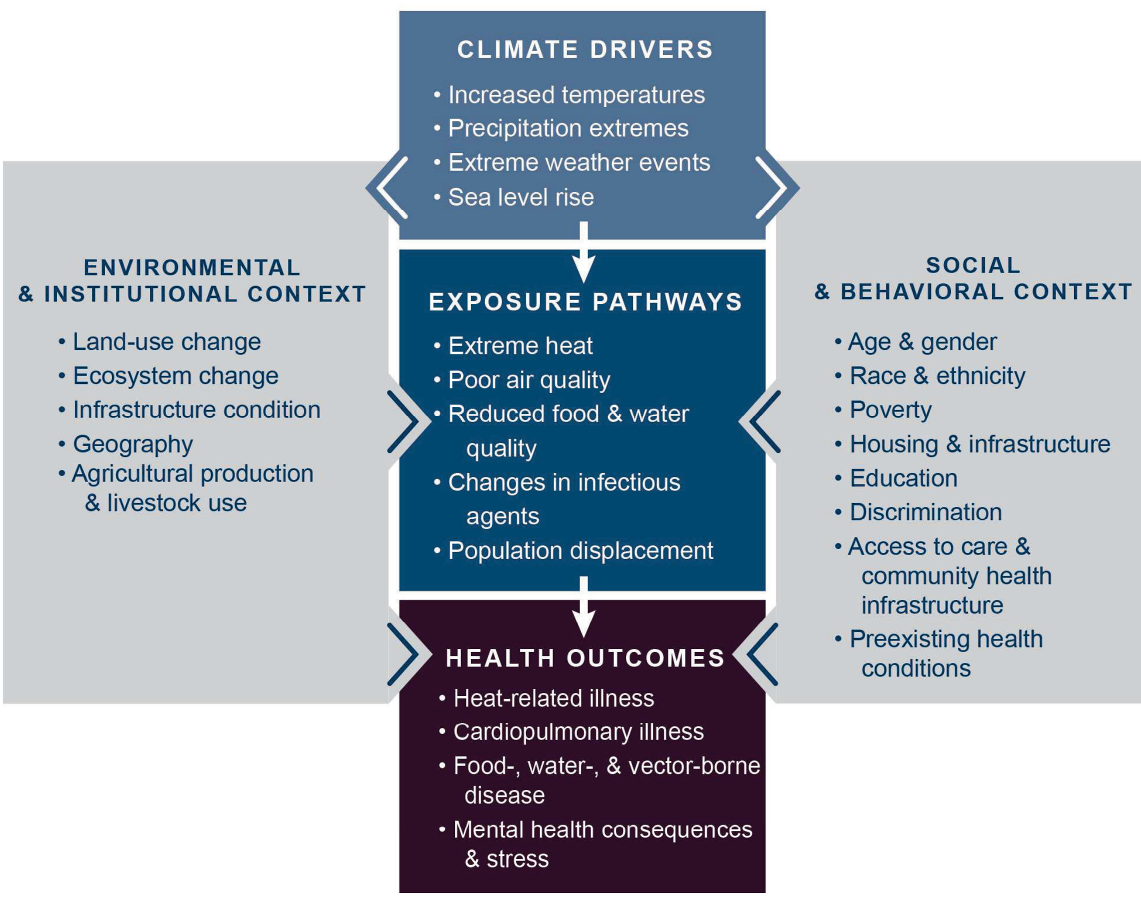


Figure 14.1: This conceptual diagram illustrates the exposure pathways by which climate change could affect human health. Exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. The extent to which climate change could alter the burden of disease in any location at any point in time will depend not just on the magnitude of local climate change but also on individual and population vulnerability, exposure to changing weather patterns, and capacity to manage risks, which may also be affected by climate change. Source: Balbus et al. 2016.[2]

The first paragraph in each of the following sections summarizes findings of the 2016 U.S. Climate and Health Assessment,[1] and the remainder of each section assesses findings from newly published research.

For example, the 2017 hurricane season highlighted the unique vulnerabilities of populations residing in Puerto Rico, the U.S. Virgin Islands, and other Caribbean islands (Ch. 20: U.S. Caribbean, Box 20.1).[9]

Extreme Events

More frequent and/or more intense extreme events, including drought, wildfires, heavy rainfall, floods, storms, and storm surge, are expected to adversely affect population health.[3] These events can exacerbate underlying medical conditions, increase stress, and lead to adverse mental health effects.[4] Further, extreme weather and climate events can disrupt critical public health, healthcare, and related systems in ways that can adversely affect health long after the event.[3]

Recent research improves identification of vulnerable population groups during and after an extreme event,[5] including their geographic location and needs (e.g. Bathi and Das 2016, Gotanda et al. 2015, Greenstein et al. 2016[6,7,8]).

Temperature Extremes

High temperatures in the summer are conclusively linked to an increased risk of a range of illnesses and death, particularly among older adults, pregnant women, and children.[18] People living in urban areas may experience higher ambient temperatures because of the additional heat associated with urban heat islands, exacerbating heat-related risks.[19] With continued warming, increases in heat-related deaths are projected to outweigh reductions in cold-related deaths in most regions.[18]

Analyses of hospital admissions, emergency room visits, or emergency medical services calls show that hot days are associated with an increase in heat-related illnesses,[20,21] including cardiovascular and respiratory complications,[22]

Box 14.1: Health Impacts of Drought and Periods of Unusually Dry Months

In late 2015, California was in the fourth year of its most severe drought since becoming a state in 1850, with 63 emergency proclamations declared in cities, counties, tribal governments, and special districts.[10,11] Households in two drought-stricken counties (Tulare and Mariposa) reported a range of drought-related health impacts, including increased dust leading to allergies, asthma, and other respiratory issues and acute stress and diminished peace of mind.[10] These health effects were not evenly distributed, with more negative physical and mental health impacts reported when drought negatively affected household property and finances.

Drier conditions can increase reproduction of a fungus found in soils, potentially leading to the disease coccidioidomycosis, or Valley fever.[3,12] Coccidioidomycosis can cause persistent flu-like symptoms, with over 40% of cases hospitalized and 75% of patients unable to perform their normal daily activities for weeks, months, or longer. Higher numbers of cases in Arizona and California are associated with periods of drier conditions as measured by lower soil moisture in the previous winter and spring.[13]

Overall, the impacts of drought on hospital admissions and deaths depend on drought severity and the history of droughts in a region.[14] Complex relationships between drought and its associated economic consequences, particularly the interactions among factors that affect vulnerability, protective factors, and coping mechanisms, can increase mood disorders, domestic violence, and suicide.[15,16,17]

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renal failure,[23] electrolyte imbalance, kidney stones,[24] negative impacts on fetal health,[25] and preterm birth.[26] Risks vary across regions (Ch. 18: Northeast, Box 18.3).[27] Health risks may be higher earlier in the summer season when populations are less accustomed to experiencing elevated temperatures, and different outcomes are observed at different levels of high temperature.[28,29] See Chapter 13: Air Quality for a discussion of the associations between temperature, air quality, and adverse health outcomes.

Vector-Borne Diseases

Climate change is expected to alter the geographic range, seasonal distribution, and abundance of disease vectors, exposing more people in North America to ticks that carry Lyme disease or other bacterial and viral agents, and to mosquitoes that transmit West Nile, chikungunya, dengue, and Zika viruses.[30,31,32] Changing weather patterns interact with other factors, including how pathogens adapt and change, changing ecosystems and land use, demographics, human behavior, and the status of public health infrastructure and management.[33,34]

El Niño events and other episodes of variable weather patterns may indicate the extent to which the risk of infectious disease transmission could increase with additional climate change.[33,35,36]

Increased temperatures and more frequent and intense extreme precipitation events can create conditions that favor the movement of vector-borne diseases into new geographic regions (e.g., Belova et al. 2017, Monaghan et al. 2016, Ogden and Lindsay 2016[31,37,38]). At the same time, very high temperatures may reduce transmission risk for some diseases.[39,40] Economic development also may substantially reduce transmission risk by reducing contacts with vector populations.[41] In the absence of adaptation, exposure to the mosquito *Aedes aegypti*, which can transmit dengue, Zika, chikungunya, and yellow fever viruses, is projected to increase by the end of the century due to climatic, demographic, and socioeconomic changes, with some of the largest increases projected to occur in North America.[31,32] Similarly, changes in temperature may influence the distribution and abundance of tick species that transmit common pathogens.[38,42,43]

Box 14.2: Transboundary Transmission of Infectious Diseases

Outbreaks occurring in other countries can impact U.S. populations and military personnel living abroad and can sometimes affect the United States. For example, the 2015–2016 El Niño, one of the strongest on record,[44] may have contributed to the 2014–2016 Zika epidemic in the Americas.[31,45,46,47,48] Warmer conditions may have facilitated expansion of the geographic range of mosquito populations and increased their capacity to transmit Zika virus.[40] Zika virus can cause a wide range of symptoms, including fever, rash, and headaches, as well as birth defects. The outbreak began in South America and spread to areas with mosquitoes capable of transmitting the virus, including Puerto Rico, the U.S. Virgin Islands, Florida, and Texas.

Water-Related Illnesses and Death

Increasing water temperatures associated with climate change are projected to alter the seasonality of growth and the geographic range of harmful algae and coastal pathogens, and runoff from more frequent and intense rainfall is projected to increasingly compromise recreational waters and sources of drinking water through increased introductions of pathogens and toxic algal blooms.[49,50,51,52,53,54]

Projected increases in extreme precipitation and flooding, combined with inadequate water and sewer infrastructure, can contribute to viral and bacterial contamination from

combined sewage overflows and a lack of access to potable drinking water, increasing exposure to pathogens that lead to gastrointestinal illness.[55,56,57,58,59] The relationship between precipitation and temperature-driven transmission of waterborne diseases is complex and site-specific, with, for example, some areas finding increased numbers of cases associated with excessive rainfall and others finding stronger associations with drought.[60,61,62,63,64,65] Heavy rainfall, flooding, and high temperatures have been linked to increases in diarrheal disease[62,64,66,67] and can increase other bacterial and parasitic infections such as leptospirosis and cryptosporidiosis.[65,68] Increases in air temperatures and heat waves are expected to increase temperature-sensitive marine pathogens such as *Vibrio*.[60,69,70,71]

Food Safety and Nutrition

Climate change, including rising temperatures and changes in weather extremes, is projected to adversely affect food security by altering exposures to certain pathogens and toxins (for example, *Salmonella*, *Campylobacter*, *Vibrio parahaemolyticus* in raw oysters, and mycotoxigenic fungi).[72]

Climate change, including changes in some extreme weather and climate events, can adversely affect global and U.S. food security by, for example, threatening food safety,[73,74,75] disrupting food availability, decreasing access to food, and increasing food prices.[76,77,78,79,80,81,82] Food quality also is expected to be affected by rising CO_2 concentrations that decrease dietary iron,[83] zinc,[84] protein,[85] and other macro- and micronutrients in crops[86,87,88] and seafood.[89,90] Projected changes in carbon dioxide concentrations and climate change could diminish expected gains in global nutrition; however, any impact on human health will depend on the many other drivers of global food security and factors such as food chain management, human behavior, and food safety governance.[91,92,93,94]

Mental Health

Mental health consequences, ranging from minimal stress and distress symptoms to clinical disorders, such as anxiety, depression, post-traumatic stress, and suicidality, can result from exposures to short-lived or prolonged climate- or weather-related events and their health consequences.[4] These mental health impacts can interact with other health, social, and environmental stressors to diminish an individual's well-being. Some groups are more vulnerable than others, including the elderly, pregnant women, people with preexisting mental illness, the economically disadvantaged, tribal and Indigenous communities, and first responders.[4]

Individuals whose households experienced a flood or risk of flood report higher levels of depression and anxiety, and these impacts can persist several years after the event.[95,96,97,98] Disasters present a heavy burden on the mental health of children when there is forced displacement from their home or a loss of family and community stability.[99] Increased use of alcohol and tobacco are common following disasters as well as droughts.[15,16,100,101] Higher temperatures can lead to an increase in aggressive behaviors, including homicide.[102,103] Social cohesion, good coping skills, and preemptive disaster planning are examples of adaptive measures that can help reduce the risk of prolonged psychological impacts.[102,104,105]

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

The health impacts of climate change are not felt equally, and some populations are at higher risk than others.[106] Low-income communities and some communities of color are often already overburdened with poor environmental conditions and are disproportionately affected by, and less resilient to, the health impacts of climate change.[106,107,108,109,110] The health risks of climate change are expected to compound existing health issues in Native American and Alaska Native communities, in part due to the loss of traditional foods and practices, the mental stress from permanent community displacement, increased injuries from lack of permafrost, storm damage and flooding, smoke inhalation, damage to water and sanitation systems, decreased food security, and new infectious diseases (Ch. 15: Tribes; Ch. 26: Alaska).[111,112]

Across all climate risks, children, older adults, low-income communities, some communities of color, and those experiencing discrimination are disproportionately affected by extreme weather and climate events, partially because they are often excluded in planning processes.[113] Other populations might experience increased climate risks due to a combination of exposure and sensitivity, such as outdoor workers, communities disproportionately burdened by poor environmental quality, and some communities in the rural Southeastern United States (Ch. 19: Southeast).[114,115,116]

Vulnerable Populations

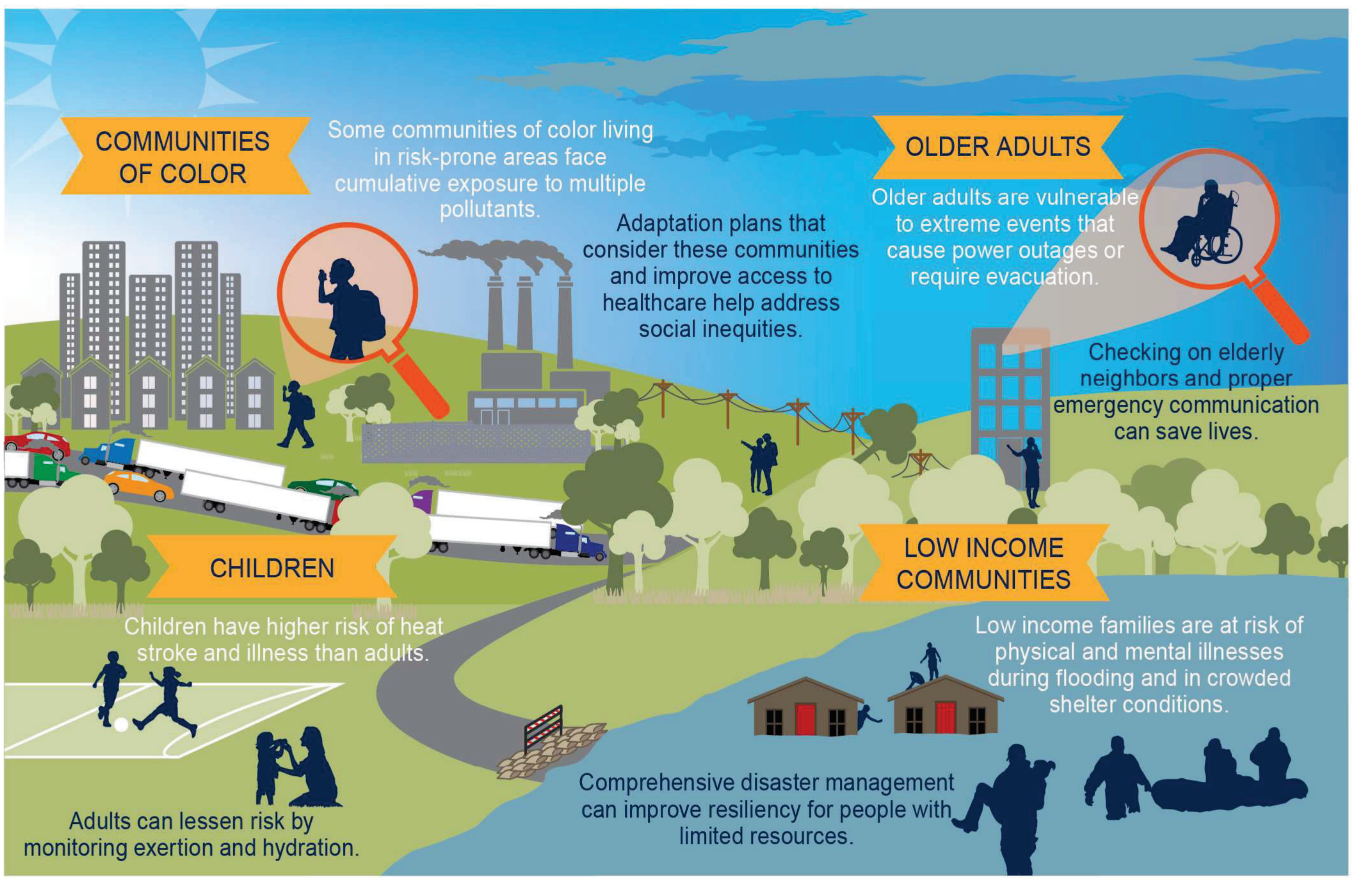

Figure 14.2: Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. Source: EPA.

Additional populations with increased health and social vulnerability typically have less access to information, resources, institutions, and other factors to prepare for and avoid the health risks of climate change. Some of these communities include poor people in high-income regions, minority groups, women, pregnant women, those experiencing discrimination, children under five, persons with physical and mental illness, persons with physical and cognitive disabilities, the homeless, those living alone, Indigenous people, people displaced because of weather and climate, the socially isolated, poorly planned communities, the disenfranchised, those with less access to healthcare, the uninsured and underinsured, those living in inadequate housing, and those with limited financial resources to rebound from disasters.[107,109,117,118] Figure 14.2 depicts some of the populations vulnerable to weather, climate, and climate change.

Building Resilient Communities

Projections of climate change-related changes in the incidence of adverse health outcomes, associated treatment costs, and health disparities can promote understanding of the ethical and human rights dimensions of climate change, including the disproportionate share of climate-related risk experienced by socially marginalized and poor populations. Such projections can also highlight options to increase population resilience.[119,120,121] The ability of a community to anticipate, plan for, and reduce impacts is enhanced when these efforts build on other environmental and social programs directed at sustainably and equitably addressing human needs.[122] Resilience is enhanced by community-driven planning processes where residents of vulnerable and impacted communities define for themselves the complex climate challenges they face and the climate solutions most relevant to their unique vulnerabilities.[110,123,124,125] A flood-related disaster in central Appalachia in spring 2013 highlighted how community-based coping strategies related to faith and spirituality, cultural values and heritage, and social support can enhance resilience post-disaster.[126]

Communities in Louisiana and New Jersey, for example, are already experiencing a host of negative environmental exposures coupled with extreme coastal and inland flooding. Language-appropriate educational campaigns can highlight the effectiveness of ecological protective measures (such as restoring marshes and dunes to prevent or reduce surge flooding) for increasing resilience. Resilience also can be built by creating institutional readiness, recognizing the importance of resident mobility (geographic movements at various scales such as commuting, migration, and evacuation), acknowledging the importance and support of social networks (such as family, church, and community), and facilitating adaptation to changing conditions.[127,128]

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Adapting to the Health Risks of Climate Change

Individuals, communities, public health departments, healthcare facilities, organizations, and others are taking action to reduce health and social vulnerabilities to current climate change and to increase resilience to the risks projected in coming decades.[129]

Examples of state-level adaptation actions include conducting vulnerability and adaptation assessments, developing comprehensive response plans (for example, extreme heat),[110,130] climate-proofing healthcare infrastructure, and implementing integrated surveillance of climate-sensitive infectious disease (for example, Lyme disease). Incorporating short-term to seasonal forecasts into public health programs and activities can protect population health today and under a warming climate.[129] Over decades or longer, emergency preparedness and disaster risk reduction planning can benefit from incorporating climate projections to ensure communities are prepared for changing weather patterns.[131]

Local efforts include altering urban design (for example, by using cool roofs, tree shades, and green walkways) and improving water management (for example, via desalination plants or watershed protection). These can provide health and social justice benefits, elicit neighborhood participation, and increase resilience for specific populations, such as outdoor workers.[107,132,133]

Adaptation options at multiple scales are needed to prepare for and manage health risks in a changing climate. For example, options to manage heat-related mortality include individual acclimatization (the process of adjusting to higher temperatures) as well as protective measures, such as heat wave early warnings,[134] air conditioning at home, cooling shelters,[135] green space in the neighborhood,[136,137] and resilient power grids to avoid power outages during extreme weather events.[138]

Early warning and response systems can protect population health now and provide a basis for more effective adaptation to future climate.[139,140,141] Improvements in forecasting weather and climate conditions and in environmental observation systems, in combination with social factors, can provide information on when and where changing weather patterns could result in increasing numbers of cases of, for example, heat stress or an infectious disease.[31,45,142,143,144] Such early warning systems can provide more time to pre-position resources and implement control programs, thereby preventing adverse health outcomes. For example, to help communities prepare for extreme heat, federal agencies are partnering with local entities to bring together stakeholders across the fields of public health, meteorology, emergency management, and policy to develop useful information systems that can prevent heat-related illnesses and deaths.[145] Adaptation efforts outside the health sector can have health benefits when, for example, infrastructure planning is designed to cool ambient temperatures and attenuate storm water runoff[146,147] and when interagency planning initiatives involve transportation, ecosystem management, urban planning, and water management.[148] Adaptation measures developed and deployed in other sectors can harm population health if they are developed and implemented without taking health into consideration.

Box 14.3: Healthcare

The U.S. healthcare sector is a significant contributor to climate change, accounting for about 10% of total U.S. greenhouse gas emissions.[149] Healthcare facilities are also a critical component of communities' emergency response system and resilience to climate change. Measures within healthcare institutions that decrease greenhouse gas emissions could significantly reduce U.S. emissions, reduce operating costs, and contribute to greater resilience of healthcare infrastructure. For example, U.S. hospitals could save roughly $15 billion over 10 years by adopting basic energy efficiency and waste-reduction measures (cumulative; no discount rate reported).[150] Combined heat and power systems can enhance hospitals' resilience in the face of interruptions to the power grid while reducing costs and emissions in normal operations.[151]

Box 14.3: Healthcare, continued

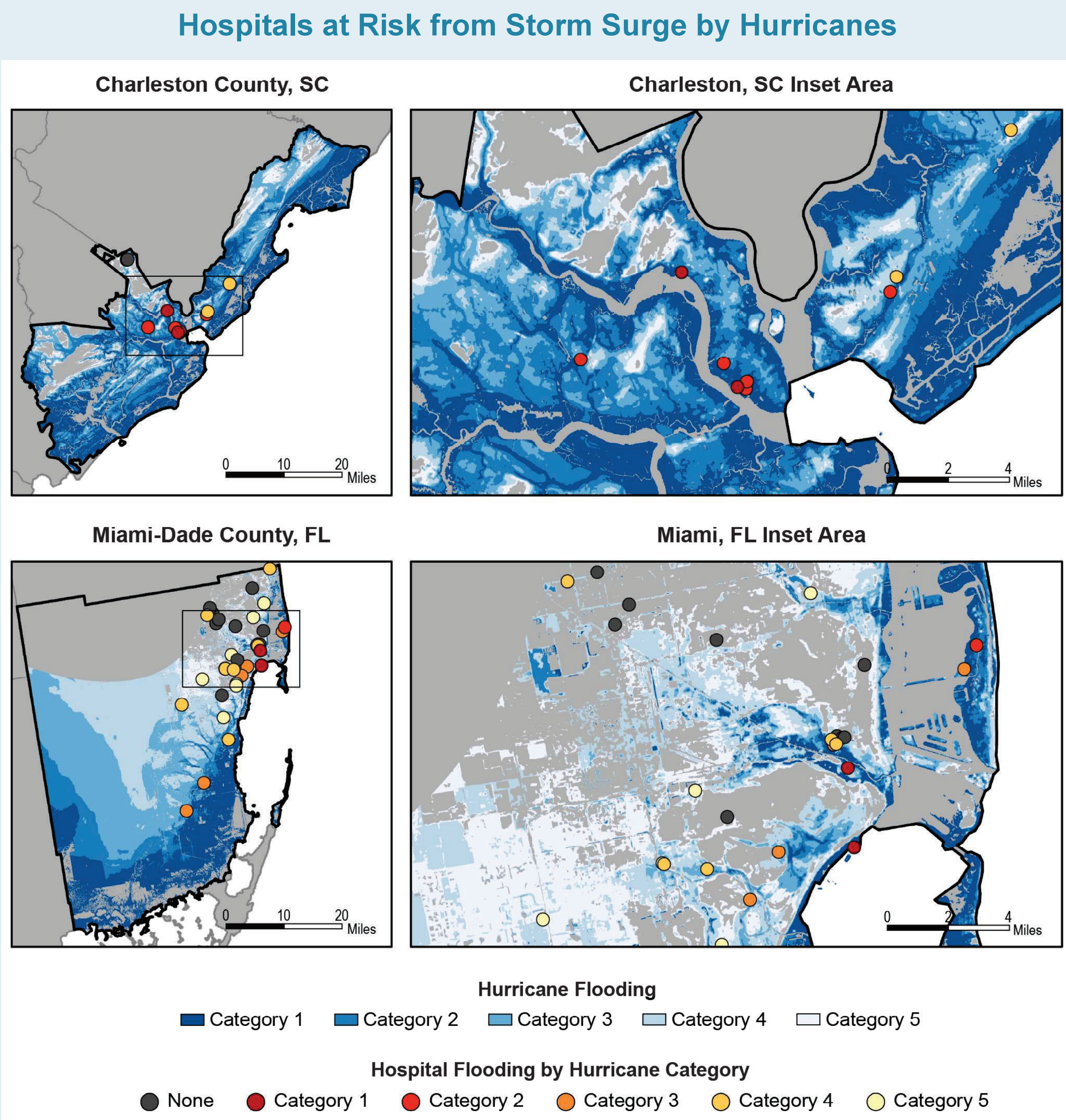

Figure 14.3: These maps show the locations of hospitals in (top) Charleston County, South Carolina, and (bottom) Miami-Dade County, Florida, with respect to storm surge inundation for different categories of hurricanes making landfall at high tide. Colors indicate the lowest category hurricane affecting a given location, with darker blue shading indicating areas with the greatest susceptibility to flooding and darker red dots indicating the most vulnerable hospitals. Four of the 38 (11%) hospitals in Miami-Dade County face possible storm surge inundation following a Category 2 hurricane; this could increase to 26 (68%) following a Category 5 hurricane. Charleston hospitals are more exposed to inundation risks. Seven of the 11 (64%) hospitals in Charleston County face possible storm surge inundation following a Category 2; this could increase to 9 (82%) following a Category 4. The impacts of a storm surge will depend on the effectiveness of resilience measures, such as flood walls, deployed by the facilities. Data from National Hurricane Center 2018[152] and the Department of Homeland Security 2018.[153]

Box 14.3: Healthcare, *continued*

In addition, healthcare facilities may benefit from modifications to prepare for potential consequences of climate change. For example, Nicklaus Children's Hospital, formerly Miami Children's, invested $11.3 million in a range of technology retrofits, including a hurricane-resistant shell, to withstand Category 4 hurricanes for uninterrupted, specialized medical care services.[151] The hospital was able to operate uninterrupted during Hurricane Irma and provided shelter for spouses and families of storm-duty staff and some storm evacuees. Assessment of climate change related risks to healthcare facilities and services can inform healthcare sector disaster preparedness efforts. For example, analyses in Los Angeles County suggest that preparing for increased wildfire risk should be a priority for area hospitals.[154]

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Reducing greenhouse gas emissions (Ch. 29: Mitigation) would benefit the health of Americans in the near and long term.[1,155] Adverse health effects attributed to climate change have many potential economic and social costs, including medical expenses, caregiving services, or lost productivity, as well as costs that are harder to quantify, such as those associated with pain, suffering, inconvenience, or reduced enjoyment of leisure activities.[156] These health burdens are typically borne by the affected individual as well as family, friends, employers, communities, and insurance or assistance programs.

Under a lower scenario (RCP4.5) by the end of this century, thousands of lives could be saved and hundreds of billions of dollars of health-related costs could be avoided compared to a higher scenario (RCP8.5).[157] Annual health impacts (including from temperature extremes, poor air quality, and vector-borne diseases) and health-related costs are projected to be approximately 50% less under a lower scenario (RCP4.5) than under a higher scenario (RCP8.5) (methods are summarized in Traceable Accounts) (see also Ch. 13: Air Quality).[37,157,158,159,160,161,162,163,164,165,166,167] The projected lives saved and economic benefits are likely to underestimate the true value because they do not include benefits of impacts that are difficult to quantify, such as mental health or long-term health impacts (see the Scenario Products Section in App. 3 for more on scenarios).

Temperature-Related Mortality

The projected increase in the annual number of heat wave days is substantially reduced under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5), reducing heat wave intensities[161,168] and resulting in fewer high-mortality heat waves[162,168] without considering adaptation (Figure 14.4). In 49 large cities in the United States, changes in extreme hot and extreme cold temperatures are projected to result in more than 9,000 additional premature deaths per year under a higher scenario by the end of the century, although this number would be lower if considering acclimatization or other adaptations (for example, increased use of air conditioning). Under a lower